SECOND EDITION

GREEN BUILDING WITH CONCRETE

Sustainable Design and Construction

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EDITED BY
GAJANAN M. SABNIS

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To my family:
Sharda
Rahul and Ann
Madhavi and Chaitanya

Contents

Preface

This book provides the most recent information about concrete's history in the green building movement, state-of-the-art methodologies, and best practices. It will appeal to several major audiences. It may be considered as a textbook for use in university courses and industry education, as a handbook for use by building owners wanting to use concrete to assist in obtaining green certification, as a reference for industry professionals seeking an overview of the subject of concrete and green buildings, and as a guide to professionals in the building materials/product industries. The concept of green buildings is in the process of emerging from a decade-long effort to define its exact meaning. There have been research, white papers, articles, and seminars on the role of concrete in the green building effort. To date, there has never been a book organized to provide an overview of the available information.

The history of cement manufacturing and the use of concrete are discussed to provide a context for today's current practices. Continuing pressures on the construction industry to reduce waste have resulted in an increase in the amount of concrete that is recycled or reused. Refurbishing or reusing structures is the least-waste option. This book outlines the variety of ways that concrete is easily and affordably reused. Work is under way within the precast industry with the aim of making it possible to lease concrete products so that they can be returned and/or reused.

The newly emerging green building delivery system now differs sharply from conventional building delivery systems. The result of this evolution has been new development and building delivery systems that emphasize a far wider collaboration among all parties to the construction process, including owners, developers, architects, engineers, constructors, facility managers, real estate professionals, and materials/product manufacturers. New quality control systems with unique requirements are one of the outcomes of the green building process, and this book will inform the reader about these requirements and the appropriate use of concrete products.

For example, LEED (US Green Building Council [USGBC], Leadership in Energy and Environmental Design) buildings must have a building commissioning component, a construction waste management system must be in place, erosion/sediment control plans must be provided and enforced, and stringent construction process requirements must be followed to ensure excellent indoor air quality for the completed building. Concrete plays a role in each of these important green building components. The USGBC's LEED green building assessment standard will be referenced often and covered in detail because it is the key to green building delivery in the United States and is also being adopted in many other countries. Environmental life cycle assessment methods conducted in accordance with ISO 14040* are described regarding their role as important emerging green building tools. This book will highlight research on economic analysis, in particular the application of life

* International Organization for Standardization, Environmental Management—Life Cycle assessment—Principles and Framework.

cycle costing, to provide a full picture of the economic benefits of concrete for a green building.

As one examines the changes and growth in infrastructure taking place around the globe, a book of this type should be based not only on the experiences in the United States and Canada but also on experience gained in Japan, Southeast Asia, and other parts of the world. With this thought, the editor looked beyond the original idea of a North American focus to find contributors from around the world. These contributions are valuable because they not only bring an international flavor but also truly embrace the concept of global sustainability. It must be affirmed that the idea of sustainability has taken on much more meaning in Southeast Asia, where countries have seriously considered this concept for centuries, compared to the few decades it has been considered in the developed world.

This book was originally written as a textbook for university classes and for the concrete industry continuing education courses taught by the National Ready Mixed Concrete Association (NRMCA) in the new course: Green Building with Concrete. This course will be available to concrete industry members all over the nation through NRMCA's extensive network of certified instructors. NRMCA also plans on partnering with state affiliates to deliver this course with member instructors who have gone through their extensive "train-the-trainer" program. This book will be an instrumental part of this special certification. The American Concrete Institute and the Portland Cement Association are both developing similar efforts. As the book took shape, the focus changed and became more global, as did the contributions. The book thus became a handbook providing diverse viewpoints from various international experts more closely matching the global nature of the sustainability movement.

This book will find its way as a textbook for courses emerging at universities on topics related to sustainable construction. California State University, Chico, offers a course* for which this book will serve as the primary textbook. The course is part of the larger concrete industry management (CIM) program, which is a relatively new 4-year degree program dedicated to meeting the employment needs of the concrete industry in the United States. Currently, four CIM programs are taught in universities in Tennessee, New Jersey, and Arizona. It is expected that they will all eventually add concrete sustainability courses.

In addition, this book serves as a tutorial for owners and developers who procure commercial and institutional buildings, including healthcare corporations, universities, school boards, manufacturers, high-technology firms, and many more entities that are recognizing the value of shifting to green building procurement and learning how to use versatile and available concrete to better meet their goals. Many green building and other green activist groups will find this book very informative and useful. These include those interested in land development, urban sprawl, brownfield recovery, and many other problems connected to industrial activity and the built environment.

Environmental Building News, World Watch magazine, and publications by organizations such as the American Institute of Architects and the Urban Land Institute

* CIMT 363. Sustainability in the Built Environment: The Role of Concrete.

would be pertinent outlets for information about this book. National agencies such as the US Environmental Protection Agency, the US Department of Energy, the US Department of Defense, the US Department of Interior, and the General Services Administration are conducting research into, promoting, and/or procuring green buildings. As a consequence, the many managers and technical staff engaged in these activities are a potential audience for this book. Additionally, the equivalents of these agencies at the state and local government levels throughout the country should have significant interest in this book because many of these organizations are procuring green buildings and writing laws and ordinances supporting the procurement of green buildings.

The book covers topics ranging from cement manufacturing to the design of concrete systems and other related topics, including rehabilitation of concrete, as they relate to sustainability. The original focus was on North American practice, but, as discussed, it was determined that the inclusion of global expertise and efforts adds substantially to the value of the text.

Following the Introduction, Chapter 2 deals with cement and its production from the sustainability perspective toward the future including an appendix that deals with admixtures, which have become an integral part of concrete. Chapter 3 is concerned with the design practice in concrete structures independent of their origin. Chapter 4 discusses the importance of concrete's thermal mass and how using special concrete can enhance overall sustainability. Chapter 5 deals with another major application of concrete in pavements, including new developments in pavements using roller-compacted concrete, the subject of Chapter 6. Chapter 7 addresses surface runoff through the application of pervious concrete for sidewalks and parking areas, where water percolation prevents flooding and maintains the level of water in soil to conserve the balance of nature. Chapter 8 focuses on how concrete applications in large metro cities can be used to mitigate urban heat island effects. Chapter 9 uses a major case study to discuss the application of sustainability in the various applications presented in earlier chapters. Chapter 10 discusses rehabilitation and the use of 3R principles, namely, reuse, recycle, and renew, so that balance is maintained by providing insight in sustainability and rehabilitation. Chapter 11 concludes with a global look at the sustainability of concrete.

The second edition was planned early in 2014 and was completed on time to present a few new chapters and additions to some. It was left to the individual contributor(s) to decide on that part. The new chapters appear at the end of the book for easy reading for those who may have the first edition already. These are essentially the new developments in the technology following the first edition. Chapter 12 was added as the recycling of concrete and the use of industrial waste have gained prominence. Chapter 13 covers the development in recycled reinforcements in concrete mainly contributed from the Concrete Reinforcing Steel Institute literature and gives additional information on the topic. Chapter 14 deals with the most recently available information on nanotechnology applications in concrete structures to make them sustainable. Finally, Chapter 15 was completed on time and with patience by its author and is gratefully acknowledged. This last chapter on sustainability is appropriately titled "Materials' Specifications: The Missing Link to Sustainability Planning."

It should be mentioned with some pride that this book is unique in some respects. With contributions from India, it shows the global relevance of sustainability, indicating that good practice is not just relevant to North America or Western Europe but also to a large country like India, where the need is even greater. Finally, the contributors have collected a large number of references in electronic form to share with the readers. More than 500 references, which add much value to the book, are available at http://www.crcpress.com/product/isbn/9781439812969. I hope that readers will acknowledge the use of these references through proper citation in their future work.

Gajanan M. Sabnis

Acknowledgments

This second edition was possible due to the great response of readers from around the world to the first edition and the resulting discussions on whether to have a reprint or new edition. It was decided in favor of the latter and I must thank Taylor & Francis Publishers, mainly Joseph Clements and his colleagues, for their patience with all of us, particularly with me in spite of delays due to health reasons and unforeseen events beyond my control that at times slowed me down.

Finally, no matter whom one acknowledges, the family is always there to support, cooperate, and withstand the hardship that goes with book projects. I have been in such situations many times! I sincerely thank my family for their usual support—in particular my wife Sharda for being at my side all the time; I say hopefully for the last time, "Thank you!"

Gajanan M. Sabnis

Editor

Gajanan M. Sabnis, PhD, PE, is an international consultant and advisor to many companies in the US and in India to help them grow globally. He is an emeritus professor at the Howard University in Washington, District of Columbia. With his diverse cultural background and experience in the United States and India, he spends considerable time in India to assist on infrastructure projects there. Large infrastructure development is taking place in India and the Middle East, and he finds it rewarding to provide such advisory service. He is a strong proponent of sustainability in civil engineering—particularly in the cement and concrete industry. He participated in the initial development of the policy on sustainability in the American Society of Civil Engineers and has built his own home in Silver Spring, Maryland, as an experiment following the principles of sustainable construction.

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1 Introduction

Gajanan M. Sabnis

CONTENTS

1.1 BACKGROUND

The advances of sustainable construction and the green building movement of the past decade have spurred a detailed examination of building materials and practices worldwide. The Portland cement and concrete industries have an invaluable role to play in achieving the goals of reducing society's environmental footprint on Earth and in the atmosphere. Cement and concrete sustainability are measured in many ways. They are measured upstream during the manufacturing process and downstream in how construction projects are built and operated.

This book offers insight into new legal, technological, and social developments guiding the introduction of green buildings and their effects on the construction industry. This includes an in-depth evaluation of carbon dioxide (CO_2) and other emissions associated with the manufacture of cement, the attributes that concrete has to offer the green building movement, and the effect that emerging life-cycle analysis has on concrete's role in this important revolution in the building industry. The chapters to follow explore the benefits of thermal mass, increased water supply, and improving water quality; reducing urban heat island effects; reducing construction waste and the use of supplementary cementitious materials to gain a better understanding of how concrete can contribute to sustainable construction; Leadership in Energy and Environmental Design (LEED); and the green building movement in general. This book outlines clearly how to make the most of concrete in sustainable design, with an emphasis on environmental impact and occupational and consumer health and safety.

1.2 INTRODUCTION

Sustainability, in general, was given a political definition by the United Nations (UN) as follows: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs—by attempting to balance social, economic and environmental effects."

One can start with this definition and work on its applicability in any field. One can hardly argue with this definition. In Section 1.3, this definition is discussed in detail. Section 1.4 covers civil engineering aspects of this definition in light of the American Society of Civil Engineers (ASCE) and the policies approved by it. Various organizations, such as the American Concrete Institute, Portland Cement Association (PCA), the Concrete Reinforcing Steel Institute (CRSI), and the Precast/Prestressed Concrete Institute, have also adopted a unified approach by establishing a coalition to pursue sustainability in the context of concrete. The Concrete Joint Sustainability Initiative is a coalition of industry associations representing companies who make or maintain concrete structures. The main goal is to educate the members of organizations at large and their clients about the use of concrete in sustainable development.

Contributions of concrete to sustainability come from its components, such as cement, aggregate, and even water, and their impact on its properties during the life of the produced structure. Concrete should be desirably strong and durable and preferably immune to any environmental factor causing its damage or deterioration. It has the ability to withstand temperature to insulate the interior, not to mention its ability to provide sound insulation in many cases, which makes it an ideal construction material anywhere the ingredients are available in the world. This brings various key issues for its sustainability, which are presented here as the main backbone for the rest of this book. They can be termed "ten commandments" to maximize concrete's sustainability. Effectively leveraged, reinforced concrete can contribute a great deal to creating sustainable buildings, bridges, and other infrastructures necessary for the successful future of any country.[1]

1.3 OVERVIEW OF THE SUSTAINABILITY MOVEMENT*

The goal of sustainability is to make the world a better place for future generations. Companies are learning that they are more profitable and more sustainable if they think in terms of a triple bottom line: *economic, social, and/or environmental profits; people; and the planet.* This approach enables business development to meet the needs of the present without compromising the ability of future generations to meet their own needs. This section provides a critical review of various historical approaches to environmental regulation and the emerging principles of sustainability.

1.3.1 Environmental Sustainability

Sustainability starts with environmental performance. While they are only one of three foundations of sustainability, environmental concerns typically get the most attention. In fact, the concepts of sustainable development and sustainability were born of environmentalism. In 1987, the UN World Commission on Environment and Development presented a document, commonly called the Brundtland Report, to the UN General Assembly. This report addressed concerns for historical development paths, which led to depleted natural resources, including clean air and water. It called for future economic development that could be sustained without depleting natural resources or harming the environment. The report famously defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[1]

The Brundtland Report was primarily concerned with global equity and the sustainable economic growth of developing nations. This concept spread through the 1990s and was expanded to the broader concept of sustainability, which can guide the philosophies and actions of individual countries, communities, industries, companies, facilities, and people, regardless of their development status.

1.3.2 Historical Command-and-Control Regulation

Before Brundtland, environmentalism relied on an adversarial system in which government entities required industrial facilities, automobiles, and communities to utilize processes or technological controls to limit air emissions, solid waste, and water discharges. This command-and-control approach sought to filter or capture pollution rather than limiting its creation. In many countries, including most in North America

* This section was contributed by Thomas B. Carter, author of Chapter 2.

and Europe, this approach was effective in removing most of the pollution from the most significant sources. For example, requiring US cement plants to install particulate matter controls reduced those emissions by more than 99%.

Most observers agree that the command-and-control approach was appropriate in the first stage of the environmental movement. From the industrial revolution of the nineteenth century until the advent of environmental awareness in the mid-twentieth century, most industries and individuals envisioned natural resources, fresh air, and clean water as limitless. By the time that humankind realized that this was not the case, dramatic steps were necessary. In the early 1970s, many governments established environmental ministries, agencies, and laws. In the last three and a half decades, industrialized countries achieved significant gains in reducing air emissions and water discharges. The initial challenge of sustainable development was to ensure that developing countries learned the lessons of the past and developed in a smarter and more environmentally aware manner.

Now that old facilities generally include emission controls—at least in developed countries—the challenge is to ensure that new facilities are designed to reduce the need for such controls. Sustainability looks beyond command-and-control measures to ensure that future development and industrialization are conducted wisely.

1.3.2.1 Beyond Compliance

One element of sustainability is that environmental policy—whether at the government or corporate level—should not be based on the rigid structure of legal requirements. Rather, these decisions should consider the long-term welfare of the people with a stake in a company or a country. As this broader approach has gathered momentum, industry and government are increasingly turning to voluntary measures to minimize environmental impacts. Often, these measures are accompanied by market-based mechanisms for ensuring that overall emissions of a given pollutant are kept to a sustainable level.

1.3.2.2 Social Sustainability

Gaining less attention than environmental concerns but equally important are the social impacts of sustainability. Sustainable industries must strive to maximize positive effects on society through education, employment, economic welfare, stakeholder empowerment, and other factors. Negative social impacts should be minimized. Social sustainability can be seen as a series of concentric circles expanding around a company of other entities.

1.3.2.3 Occupational Health and Safety

At the center of sustainable industries and companies are individual employees. The health, safety, and welfare of employees and the communities in which they live and work are essential components of economic, environmental, and societal factors by which sustainability decisions are weighed.

1.3.2.4 Community Health and Safety

Controlling emissions, waste, and discharges is essentially a community health and safety program—and, in the case of greenhouse gases or other pollutants with broader consequences, a global health and safety program. Therefore, the environmental sustainability steps discussed before are directly relevant to community concerns.

Other community health and safety issues include safe quarry operations and safe driving and rail operation guidelines. Less direct but equally important contributions include sponsorship of local youth athletic programs and health care benefits for employees and their families. Finally, the very act of employing community members contributes to their ability to obtain good nutrition and medical care and to their general physical and mental health. All of these are factors by which the cement industry creates sustainable communities.

1.3.2.5 Customer Health and Safety

The next ring of social sustainability includes the customers and users of cement. One form of outreach to this group is sharing of information on the contents of the product. For example, in the United States, manufacturers provide their customers with a material safety data sheet with detailed information on any health or safety concern associated with ingredients in cement.

1.3.2.6 Community Involvement

A mark of social sustainability that extends beyond health and safety is stakeholder involvement. Many companies have established community involvement committees to give their neighbors a voice in major decisions that might affect the community. An informed and participatory community can make the right decisions to become a sustainable community.

1.3.3 Economic Sustainability

The final leg is economic sustainability. For a company to remain a valuable member of the community in which it operates and to contribute to environmental and social sustainability, it must remain in business. This requires operating at a long-term profit.

1.3.3.1 Cost Savings

Many of the measures taken to achieve environmental and social sustainability directly benefit the financial bottom line and therefore contribute to economic sustainability. Air emissions, solid waste, and water discharges are the results of inefficiencies in an industrial system. An ideal system would produce no waste or by-products. While generally unattainable, this is still the ultimate goal of a sustainability program. Enhancing energy efficiency, minimizing waste, and utilizing industrial by-products as fuels or raw materials improve both profits and the environment.

1.3.3.2 Stakeholder Satisfaction

Another means by which a company can ensure financial sustainability is to maximize the satisfaction of its employees, customers, communities, shareholders, and other stakeholders. Taking care of employees and being a good community member are two ways to achieve stakeholder satisfaction. Having a strong record of striving toward environmental and social sustainability is increasingly important in attracting and pleasing customers, communities, shareholders, and other stakeholders.

1.4 SUSTAINABILITY AND CIVIL ENGINEERING

Civil engineers looked at sustainability as a policy and principle of practice. For the first time after years of debate, as a professional body, ASCE has revised its Code of Ethics to make the principles of sustainable development part of the canon of civil engineering practices and introduced it as a policy statement that is continuously updated.

The concept of sustainability will deal primarily with sustainable development as defined by the ASCE in 1996: "Sustainable Development is the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development."[2]

Sustainability in the developed as well as in the developing world requires scientific and technical innovations to create designs that enable the earth and its inhabitants to prosper and therefore should be considered as a universal phenomenon.

ASCE encourages the use of *life-cycle cost analysis (LCCA) principles* in the design process to evaluate the total cost of projects. The analysis should include planning, design, construction, operation, maintenance, regulatory, environmental, safety, and other costs that are reasonably anticipated during the life of the project, whether borne by the project owner or those otherwise affected. When the cost of a project is estimated only for design and construction, the long-term costs associated with maintenance, operation, and retiring of a project are overlooked. One of the most significant elements for the planning and designing of facilities is the determination of the total effect of life-cycle costs on a project. The rationale in the use of LCCA is to raise the awareness of owners, clients, and the public of the total costs of projects and promote quality and comprehensive engineering solutions. Short-term design cost savings that lead to high future costs will be exposed as a result of the analysis.[3]

1.5 SOME MYTHS ABOUT SUSTAINABILITY[4]

The sustainability and green building movements have given rise to more discussion on the topic and created some critical issues, which may or may not be significant. This section takes a critical, hard look at some myths about sustainability and concrete from a global perspective.

1.5.1 Sustainability Is a New Phenomenon

Sustainability as introduced now in our life may be new, but it was always part of our engineering works. Thus, if the structure is designed well and the makers follow certain engineering guidelines, it will be sustainable. Sustainability has moved into our lives and will remain with us. Professionally speaking, ASCE was the first to adopt sustainability as a policy in 1996 to cover civil engineering principles for the profession to follow. In 2010, the US General Services Administration (GSA) established the position of chief greening officer, who is responsible for pursuing innovative and sustainable practices within his or her domain of buildings. On the other hand, it has been shown that it does not cost more to convince clients to embrace green principles via sustainable construction. Later, the American Institute of Architects also adopted similar principles. The US Green Building Council (USGBC) has also made an impact on the profession, showing the very high rate of growth in all aspects of the green movement and sustainability.

In today's society, the idea of sustainability is possibly more prevalent than at any other point and time. Across our everyday lives, we encounter the practice of sustainability from renewable energy resources to curbside recycling programs. As our demand for products, infrastructure, and lifestyle amenities grows, so should our awareness that we live in a fragile balance between meeting these needs and meeting them in a way that has minimal impact on the environment and does not jeopardize our own public health and safety.[5] Civil engineers and future civil engineers play a vital role in sustainable development in meeting the needs of the public. Their design and building of infrastructures support our society.

1.5.2 Sustainability Is an Intrinsic Part of Our Educational System

Future generations must become aware of sustainability as early as possible in their lives since they will be faced with the problems when they become part of the profession. Earlier in education, teachers should make them aware of following the "3 Rs" (renew, restore, reuse). Events such as the bridge collapse in Minneapolis, the ever-growing demand for transportation infrastructure, a continuing increase in population, and concerns of global warming have made educating new engineers on the concept of sustainable development ever more important. Today's civil engineering students are exposed to the need for sustainable development from many directions.

University professors should incorporate sustainable development into the curriculum to make it consistent with the times. The institution and individual faculty members must ensure that students are being educated on practicing sustainable development. On the other hand, students have an ethical responsibility to take the principle of sustainable development and carry it on into their professional careers. This will happen only with a clear understanding of the importance of sustainable development and its application in their future jobs.[5]

Only a handful of firms use the sustainable solution on the entire project from concept to reality (completion). Sustainability will change with the times and with constantly advancing practices and use of new and better products and technology applications. Construction professionals need to make an effort to learn about new opportunities for making their products more sustainable.

1.5.3 Sustainable Structures Cost More

A 1996 residential project[6] with several sustainable elements showed that the cost was only marginally higher and was economically based on the life-cycle cost analysis. This was before sustainability became a buzzword. The project used as many sustainable features as possible, including the use of recycled materials, insulated concrete, geothermal energy, and green materials. The efficient use of energy saved money toward the cost of installing better heating and cooling systems. Many other projects can be cited with similar results. In some projects, sustainable floor products that cost less than conventional ones are sometimes used. We can use the LEED certification to make ourselves feel good without spending a great deal of money.

1.5.4 Products That Claim to Be "Green" Are Sustainable

Since following the green wave has rapidly become "the thing to do," many companies are claiming to have green products. Although various standards for green do exist, gaps and conflicts make it tricky to monitor the efficiency and effectiveness of the products and systems. Consumers must be careful when purchasing products claiming to be sustainable. For example, although there are many product options for carpet backing, acoustical ceiling tiles, and other finishes made with postconsumer recycled content, this does not mean that, once in a house, they save energy. Recent research has revealed that many products that received the Energy Star seal did not really live up to their hype. Why? The US Environmental Protection Agency, which oversees the program, was overloaded with products to review and became inefficient.

1.5.5 Government and the Public Do Little to Enhance Sustainability

Within the borders of the United States, development projects that are undertaken by government agencies are held under a microscope to the practice of sustainable development. Any time a government agency puts a project out for bid, the requirements of that project are in line with the practice of sustainable development. Projects above a certain value are also evaluated for LCA as a mandatory evaluation mode to make the structure a real sustainable product.

The US Department of State sponsors sustainable development partnerships that reach not only across this country[7] but also beyond our borders. These partnerships with foreign countries allow them to look at the project from a global concern, with information and technology to provide poverty reduction programs such as universal primary education; access to clean water and sanitary systems; access to energy services; reducing the spread of infectious diseases; reducing hunger and promoting agricultural and rural development, conservation, and environmental stewardship; and protecting marine and freshwater resources. These partnerships provide a two-way exchange of information between the two countries to enhance the health, safety, and well-being of their citizens in addition to giving them a greater awareness of environmental impacts with the information and technology.

Civil engineers have a very unique duty to society and a responsibility to advance the infrastructures of the society in a way that not only meets the demand needs but also does so in a socially responsible manner. Professionally, there must be a proper push forward to meet the needs of an ever-growing and ever-changing society. This will lead to a way to design and practice within the civil engineering field in a manner that is always ethical and true to the practice of sustainable development.

1.6 LIFE-CYCLE IMPACT: CREATING A SUSTAINABLE PRODUCT*

A sustainable industry should be marked by a minimal environmental impact not only during the manufacturing process but also during the entire life cycle of the product. Cement and concrete products fare very well in life-cycle analyses. Concrete is highly durable, and concrete buildings and pavements are more energy efficient than those made with competing products.

Durability is a key attribute. A longer-lasting product will be manufactured and applied fewer times. Concrete will not rust, rot, or burn and requires less energy and fewer resources over time to repair or replace it. Concrete builds durable, long-lasting structures including sidewalks, building foundations, and envelopes, as well as roadways and bridges. Incorporating the most widely used building material in the world, concrete structures have withstood the test of time for more than 2000 years. Because of its longevity, concrete can be a viable solution for an environmentally responsible design.

Concrete also creates more energy-efficient structures than other building materials do. Homes and buildings constructed from insulated concrete walls are not subject to large daily temperature fluctuations. This means home or building owners can lower heating and cooling bills up to 25% and that occupants within these structures are more comfortable. Also, heating, ventilating, and air conditioning can be designed with smaller capacity equipment.

Additionally, concrete minimizes the effects that produce urban heat islands. Studies have shown that urban environments have higher temperatures in areas where there are few trees and a multitude of paved surfaces and buildings. This additional heat causes air-conditioning systems to work harder, which uses more energy (up to 18% more) and promotes the formation of smog. Light-colored concrete absorbs less heat and reflects more light than dark-colored materials, thereby reducing heat gain. Light-colored pavements also require less site lighting to provide safe nighttime illumination levels on parking lots, driveways, or sidewalks.

Several studies have shown that vehicles get better gas mileage traveling on concrete pavements than on other materials. Concrete's rigid surface creates less drag, particularly in hot weather, when asphalt becomes even softer.

Another factor in examining life-cycle greenhouse gas impacts of concrete is its ability to reabsorb significant levels of CO_2 over its lifetime. This carbonation process actually reverses the chemical calcination process that takes place during cement manufacturing. While other building and paving materials can release greenhouse gases and other pollutants over their lifetime or at destruction, concrete actually serves as a carbon sink.

These end-use energy savings are a crucial portion of PCA's greenhouse gas reduction program. Although the energy savings experienced by users of concrete do not count toward the industry's goal of reducing CO_2 from the manufacturing process, they could offset greenhouse gas emissions from the manufacture of the product.

* This section was contributed by Prof. Dr. Siti Hamisah Tapsir, Technical University of Malaysia, Kuala Lumpur.

In other words, if concrete is utilized in a way to enhance its energy efficiency, the industry could become a net sink of CO_2 as opposed to a source.

Concrete can also play a role in enhancing water quality and quantity. Pervious concrete surfaces enable storm water to pass through the pavement and its base. These innovative surfaces have a number of environmental benefits. Traditional impervious pavements collect storm water from a large surface and concentrate it into runoff points, resulting in flooding risks. Pervious pavements recharge the aquifer by allowing rainwater to soak into the ground where it falls, as it would in nonpaved areas. Rather than washing the residues of vehicle and other emissions into local waterways, pervious pavements provide an initial filter of these pollutants before they enter the ground, where they can be further filtered. Pervious concrete provides a cleansing and durable access point for storm water to recharge the aquifer, whereas competing oil-based and chemically sealed materials can add to water pollution, and softer materials can get compressed, reducing their pervious characteristics.

Recycling also factors into cement's life-cycle analysis during the cement manufacturing process and in the production, use, and disposal of concrete. Many wastes and industrial by-products such as fly ash that would otherwise clog landfills can be added to concrete mixes. These by-products also reduce reliance on raw materials. For example, in 2001, the concrete industry used 11,400,000 tonnes of fly ash—a by-product of coal combustion at electric power utility plants.

Finally, when a concrete structure has served its purpose, it can be recycled as aggregate in new concrete paving or backfill or as road base. Even the reinforcing steel in concrete (which is often made from recycled steel) can be recycled and reused. Concrete is easy to use and can be readily recycled. Delivered and prepared for each specific project, concrete typically produces very little waste.

1.7 ENVIRONMENTAL CONCERNS

Discussion of sustainability in the context of engineering, especially for cement and concrete, leads to a number of environmental concerns. Although several of these are treated in detail in later chapters, initial comments are in order in the introduction.

Concrete has been used for hundreds of years in all parts of the world and has provided mankind with the safest and most durable and sustainable building material. It provides superior fire resistance, gains strength over time, and has an extremely long service life. Concrete is the most widely used construction material in the world, with annual consumption estimated at between 20 and 30 billion tonnes. Concrete construction minimizes the long-term costs of a building or of infrastructure projects for reconstruction. Its ingredients are cement and readily available natural materials: water and aggregate (sand and gravel or crushed stone). Concrete does not require any CO_2-absorbing trees to be cut down. The land required to extract the materials needed to make concrete is only a fraction of that used to harvest forests for lumber.

1.7.1 CO_2 Emissions and Global Change

The cement industry is one of two primary producers of carbon dioxide (CO_2), creating up to 5% of worldwide man-made emissions of this gas, of which 50%

is from the chemical process and 40% from burning fuel.[8] The embodied carbon dioxide (ECO_2) of 1 tonne of concrete varies with mix design and is in the range of 75–175 kg CO_2/tonne concrete.[9] The CO_2 emission from the concrete production is directly proportional to the cement content used in the concrete mix. Indeed, 900 kg of CO_2 are emitted for the fabrication of every ton of cement.[10] Cement manufacture contributes greenhouse gases directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide,[11] as well as through the use of energy, particularly from the combustion of fossil fuels. However, some companies have recognized the problem and are envisaging solutions to counter their CO_2 emissions. The principle of carbon capture and storage consists of directly capturing the CO_2 at the outlet of the cement kiln in order to transport it and to store it in an adequate and deep geological formation. Chapter 2 deals in depth with these many issues.

1.7.2 Surface Runoff

Surface runoff (when water runs off impervious surfaces, such as nonporous concrete) can cause heavy soil erosion. Urban runoff tends to pick up gasoline, motor oil, heavy metals, trash, and other pollutants from sidewalks, roadways, and parking lots.[11,12] The impervious cover in a typical city sewer system prevents groundwater percolation five times that of a typical woodland of the same size.[13] A 2008 report by the US National Research Council identified urban runoff as a leading source of water quality problems.[14] This problem needs to consider the possibilities using a recently developed pervious concrete. This aspect is considered in detail in Chapter 7.

1.7.3 Urban Heat

Both concrete and asphalt contribute to the urban heat island effect. The use of light-colored concrete is effective in reflecting up to 50% more light than asphalt, thus reducing ambient temperature.[15] A low albedo value, characteristic of black asphalt, absorbs a large percentage of solar heat and contributes to the warming of cities. By paving with light-colored concrete, in addition to replacing asphalt with light-colored concrete, communities can lower their average temperature.[16]

Pavements comprise approximately 30%–40% of the surface area[15] and thus directly impact the temperature of the city, as demonstrated by the urban heat island effect. In addition to decreasing the overall temperature of parking lots and large paved areas by paving with light-colored concrete, there are supplemental benefits, such as 10%–30% improved nighttime visibility.[15] There is a high potential to save energy within the area. With lower temperatures, the demand for air conditioning decreases and consequently saves vast amounts of energy.

Pavement technology is rapidly evolving and is applied especially in developing countries. Developed countries that have focused on developing road infrastructure have gained substantial experience that can be shared with developing countries in order to offer global sustainability benefits. Chapters 5 and 6 discuss pavement applications with concrete that have credentials to offer multitudes of sustainability benefits. The concrete material and construction technique discussed in these chapters cover the classical one with roller-compacted concrete. These material and construction techniques offer cement savings, can accommodate a range of aggregates, require less mechanization, reduce the overall cost substantially, and have better durability.

Atlanta and New York City can be cited for their efforts to mitigate the heat island effect. City officials noted that when heat-reflecting concrete was used, the average city temperature decreased by 6°F.[17] The Design Trust for Public Space in New York City found that, by slightly raising the albedo value in the city, beneficial effects such as energy savings could be achieved. This could be accomplished by replacing the black asphalt with light-colored concrete. In winter, this may be a disadvantage because ice will form more easily and remain longer on the light-colored surfaces, which will be colder due to less energy absorbed from the small amounts of sun in winter.[16] More details on the subject are covered in Chapter 8.

1.7.4 Health Concerns

The presence of some substances in concrete, including useful and unwanted additives, has raised some health concerns. Natural radioactive elements (K^{19}, uranium [U], and thorium [Th]) can be present in various concentrations in concrete dwellings, depending on the source of the raw materials used.[18] Toxic substances may also be added to the mixture for making concrete by unscrupulous makers. Dust from rubble or broken concrete upon demolition or crumbling may cause serious health concerns depending also on what was incorporated in the concrete. Global concerns on these issues are considered in detail in Chapter 11.

1.7.5 Concrete Handling/Safety Precautions

Handling of wet concrete must always be done with proper protective equipment. Contact with wet concrete can cause skin burns due to the caustic nature of the mixture of cement and water. Water may seep through the concrete, often in cracks, having dissolved components of cement stone. Osteoporosis of concrete often happens in parking garages as road salt comes off cars to the concrete floor as a saline solution in the winter.

1.7.6 Concrete Repair

Concrete repair applies to both concrete structures and pavements. Concrete pavement preservation (CPP) and concrete pavement restoration (CPR) are techniques used to manage the rate of pavement deterioration on concrete streets, highways, and airports. Without changing concrete grade, this non-overlay method is used to repair isolated areas of distress. CPP and CPR techniques include slab stabilization, full- and partial-depth repair, dowel bar retrofit, cross-stitching longitudinal cracks or joints, diamond grinding, and joint and crack resealing. CPR methods, developed over the last 40 years, are utilized in lieu of short-lived asphalt overlays and bituminous patches to repair roads. These methods are often less expensive than an asphalt overlay; they last three times longer and provide a greener solution.[19] CPR techniques can be used to address specific problems or bring a pavement back to its original quality. When repairing a road, design data, construction data, traffic data, environmental data, previous CPR activities, and pavement condition must all be taken into account. CPR methods extend pavement life beyond 15 years.

Concrete structures need to be looked at from a sustainability perspective for preservation and for extending their lives. Damage is a cumulative phenomenon and affects the structure over a long period. Depending on the national security perspective, such structures need to be monitored for strength and durability.

1.7.7 Energy Efficiency[20]

Energy requirements for transportation of concrete are low because it is produced locally from local resources, typically manufactured within 100 km of the job site. Once in place, concrete offers significant energy efficiency over the lifetime of a building.[21] Concrete walls leak air far less than those made of wood frames. Air leakage accounts for a large percentage of energy loss from a home. The thermal mass properties of concrete increase the efficiency of both residential and commercial buildings. By storing and releasing the energy needed for heating or cooling, concrete's thermal mass delivers year-round benefits by reducing temperature swings inside and minimizing heating and cooling costs. While insulation reduces energy loss through the building envelope, thermal mass uses walls to store and release energy. Modern concrete wall systems use both insulation and thermal mass to create an energy-efficient building. Insulating concrete forms (ICFs) are hollow blocks or panels made of insulating foam forms that are stacked to create any shape of the walls of a building and then filled with reinforced concrete to create the structure. This energy aspect is discussed in detail in Chapter 4.

1.7.8 Fire Safety and Quality of Life[20]

Concrete buildings are more resistant to fire than those constructed using wood or steel frames. Since concrete does not burn and stops fire from spreading, it offers total fire protection for occupants and their property. Concrete reduces the risk of structural collapse and is an effective fire shield, providing safe means of escape for occupants and protection for firefighters. Furthermore, it does not produce any smoke or toxic gases and does not drip molten particles, which can spread fire. Neither heat and flames nor the water used to extinguish a fire seriously affects the structure of concrete walls and floors, making repairs after a fire a relatively simple task.

A limited study conducted in Sweden by Olle Lundberg on the cost of fire damage associated with larger fires in multi-unit buildings and based on statistics from the insurance association in Sweden (Försäkrings Förbundet) had some interesting conclusions. The study covered 125 fires over a 10-year period between 1995 and 2004. Only 10% of the fires were in multifamily homes; however, 56% of the fires were major. The results showed the following:

- The average insurance payout per fire per unit in wood-frame buildings was around five times that of fires in concrete buildings (approximately $60,000 compared with $12,000).
- A major fire is more than 11 times more likely to develop in a wood-frame house than in one built using concrete.
- Among the burned houses, 50% of those made with wood had to be demolished, whereas only 9% of the concrete ones were beyond repair.
- The fire spread to neighboring buildings in only 3 of the 55 fires in concrete houses.
- Of those 55 fires, 45 were in attics and roofing.

Options for noncombustible construction include floors, ceilings, and roofs made of cast-in-place and hollow-core precast concrete. For walls, concrete masonry technology and ICFs are additional options. Insulating concrete forms are hollow blocks or panels made of fireproof insulating foam that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

"Fire–wall" tests, in which ICF walls were subjected to a continuous gas flame with a temperature of more than 1000°C for as long as 4 h, showed no significant breaks in the concrete layer or dangerous transmission of heat. In comparison, wood-frame walls normally collapse in an hour or less under these conditions. Concrete provides stable compartments in large industrial and multistory buildings, so a fire starting in one section does not spread to others. Thus, concrete provides an excellent material for building construction and offers the best possible protection and safety in fires:

- It does not burn or add to fire load and has high resistance to fire, preventing it from spreading and thus reducing the resulting environmental pollution.
- It does not produce any smoke or toxic gases or drip molten particles; it resists extreme fire conditions, making it ideal for storage facilities with a high fire load.
- It reduces the risk of structural collapse and thus provides a safe means of escape for occupants and access for firefighters because it is an effective fire shield.
- It is not affected by the water used to put out a fire.
- It is easy to repair after a fire and thus helps residents and businesses recover sooner.
- It provides complete fire protection, so there is normally no need for additional measures.

In addition, concrete provides the best resistance of any building material to high winds, hurricanes, and tornadoes due to its stiffness, which results in minimal horizontal movement. When properly designed for ductility, it also provides superior resistance to seismic events. It does not rust, rot, or sustain growth of mold and stands up well to the freeze–thaw cycle. As a result of all these benefits, insurance for concrete homes is often 15%–25% lower than for comparable wood-frame homes.

Because concrete buildings also have excellent indoor air quality with no off-gassing, toxicity, or release of volatile organic compounds (VOCs), they are generally healthier to live in than those made of wood or steel. It is practically inert and waterproof, so concrete does not need volatile organic-based preservatives special coatings or sealers. Concrete can be easily cleaned with organic, nontoxic substances. Its sound-insulating properties make buildings and homes a quiet and comfortable living environment. After accounting for sound passing through windows, a concrete home is about two-thirds quieter than a comparable wood-frame home.[22]

Due to the extended life of concrete structures, their impacts on the environment are negligible. Once built, they require minimal maintenance and result in very little social disruption. Concrete reduces construction waste because it is used only on an as-required basis, thereby minimizing the waste put into landfills.

1.8 TEN QUALIFICATIONS OF CONCRETE FOR SUSTAINABILITY[1]

This chapter is appropriately closed with a summary of concrete, which is an excellent and globally available construction material with its 10 best qualities to be the sustainable material. The CRSI[1] describes these qualities in a different form; these are appropriately modified.

1. *Long service life.* Reinforced concrete's durability ensures that the structure will retain its structural and aesthetic capabilities for many years. The carbon footprint of a structure is minimized when the need to replace it is eliminated completely.
2. *Safety.* Reinforced concrete structures can withstand natural disasters, including hurricanes, tornadoes, earthquakes, and floods. This resistance minimizes the need for replacement or repair.
3. *Energy efficiency.* Reinforced concrete's inherent thermal mass absorbs heat during the day and releases it at night, reducing heating, ventilating, and air conditioning (HVAC) costs and enhancing energy efficiency.
4. *Lower maintenance.* Reinforced concrete provides long-term durability and therefore minimizes the need of extensive maintenance when compared with other materials of construction. Because cast-in-place reinforced concrete offers a monolithic approach to design, few or no joints or connections need to be maintained.
5. *Reduced waste.* Concrete components typically are cast as specified, with little excess produced. What waste accrues through cutouts, change orders, etc., can be recycled.
6. *Minimized harvesting impact.* Concrete producers can replace significant amounts of cement in their mixtures with industrial by-products such as silica fume and blast furnace slag. Their use in concrete removes them from landfills and minimizes cement use while, in many cases, producing an even more durable concrete.
7. *Minimized transportation cost.* Virtually all of reinforced concrete components can be made locally anywhere in the world. This turns out to be the key element in reducing emissions due to transportation. Through the

utilization of local materials, the impacts of transportation are minimized. Concrete components typically are cast as specified, with little excess produced. What waste accrues through cutouts, change orders, etc., can be recycled and in turn results in reduced waste.

8. *Design flexibility.* Reinforced concrete offers flexibility to design dramatic architectural shapes with long-span capability that can deliver open interior layouts, creating flexibility in designing spaces and providing the ability to install equipment quickly. Design efficiency also often reduces floor heights. In turn, concrete framing systems offer substantially lower floor-to-floor heights, creating energy-efficient designs that may be able to add revenue-generating floors to the building while meeting zoning restrictions on height.
9. *Improved indoor air quality.* Concrete contains no VOCs, and this improves indoor air quality. It does not support mold growth because it is inorganic. The monolithic nature reduces hidden spaces where insects, rodents, and biological hazards can accumulate and infiltrate into occupied spaces. The impervious barrier provided by reinforced concrete helps keep the outdoors outside and lets the interior environment be controlled by the HVAC systems.
10. *Aesthetics and other significant social benefits.* Reinforced concrete can be cast in almost any surface finish or shape. This provides the designer with unlimited flexibility with color, shape, and texture. In addition, concrete provides high fire resistance and excellent sound insulation. It thus creates safe, secure, and comfortable designs. Combined with its ability to provide high wind resistance and indoor comfort, reinforced concrete can help boost productivity and worker satisfaction and offer a higher-quality, "greener" way of life.

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2 Sustainability in the Cement Industries and Chemical Admixtures

Thomas B. Carter

CONTENTS

2.1 PREVIEW

Cement manufacturing is a complex and massive industrial process undertaken by large organizations. With the exception of small quantities of masonry cement and other specialty cements, all cement is called Portland cement and used as the key ingredient of concrete, which is used in greater volumes than any other manufactured material on earth. Cement is the agent that binds together the fine and coarse aggregate components of concrete when combined with water. Since it requires intense heat, cement manufacturing involves significant fossil fuel combustion and therefore creates carbon dioxide and numerous other pollutants. Improving concrete's sustainability will require measures in all stages of the product's life cycle—from the manufacture and shipment of cement to the blending and application of concrete—to reduce energy use, capture and utilize emissions from cement manufacturing and other processes, and build energy-efficient and long-lasting structures. Perhaps concrete's greatest promise lies in its applications in sustainable buildings.

While cement manufacturing has become somewhat more energy efficient in the past several decades, the basic process has not fundamentally changed since its invention in the nineteenth century, nor have the basic ingredients of concrete, although there have been efforts to reduce the cement portion by partially supplanting it with supplementary cementitious materials (SCMs). Another change has been the increased use and sophistication of chemical admixtures, which have gained a rather pivotal and quite an influential profile in concrete making.[1,2]

2.2 INTRODUCTION

Cement manufacturing is a large industrial process that requires significant inputs of raw materials and energy. Yet, the primary fate of cement is to serve as a key ingredient in concrete, which can be a highly sustainable building and paving material. Cement plants have historically emitted significant quantities of particulate matter, nitrogen oxides, and other gaseous and solid wastes. Some plants have also produced discharges of process water and storm water. In the past few decades, cement manufacturing companies around the world have worked hard to reduce the environmental impact of this process, but the environmental footprint of cement—and thus of concrete—remains significant.

While some of the improvements have been driven by legal requirements, many industry programs look beyond simply regulatory compliance or even the broader issue of environmental performance. When assessing the impacts of products and activities, the focus has shifted in recent years to sustainability, a holistic perspective that encompasses environmental impact, raw material use, community involvement, worker and customer health and safety, energy use, and economic performance.

The global cement manufacturing industry has embraced sustainability and the triple bottom line: economic, social, and environmental. An example of this focus is the Cement Sustainability Initiative, a global effort under the auspices of the World Business Council for Sustainable Development. There have also been multiple sustainability programs in the United States and other individual countries that involve both the cement and concrete industries.

Sustainability also examines the impacts of a product throughout its lifetime. Life-cycle analysis assesses not just the environmental impact of manufacturing a product but also its use and disposal. Concrete performs well under life-cycle analysis. While the initial manufacturing impact—particularly that associated with the cement component—might be greater than those of competing materials, concrete has a long life span and can enhance the energy efficiency of buildings and pavements over that entire duration. This chapter will examine the principles of sustainability, with emphasis on the applicability to concrete and its ingredients.

2.3 ROLE OF CEMENT AND CONCRETE IN CLIMATE CHANGE

Perhaps the most significant environmental issue facing the world today is the buildup of greenhouse gases (GHGs) in the atmosphere and the associated threat of global climate change. The cement and concrete industries have key roles in this issue but on opposite sides of the coin. Cement manufacturing is a significant source of CO_2 emissions, the primary GHG of concern. Yet concrete can reduce energy use—and thus associated GHG emissions—over its lifetime and can even absorb carbon dioxide directly into the product.

Cement manufacturing accounts for roughly 5% of global anthropogenic GHG emissions. The making of cement emits CO_2 in two ways. Calcination emissions are the result of the conversion of calcium carbonate ($CaCO_3$) to calcium oxide (CaO), which is the essential ingredient of cement. A simple mass balance reveals that this transformation liberates a molecule of CO_2. The calcination process requires extreme heat, up to 2700°F, requiring combustion. Most cement plants use coal to fire their kilns. As a general rule, cement manufacturing produces 1 ton of CO_2 for each ton of product. These emissions are generally split fairly evenly between calcination and combustion emissions, although more efficient plants have a lower proportion of combustion emissions.

The cement industry is striving to reduce its CO_2 emissions in several ways. Combustion emissions can be reduced by maximizing the efficiency of the manufacturing process. Modern kilns introduce a dry raw material mix to precalciners that utilizes waste heat to shorten the kiln time and dramatically reduce combustion needs. This is in contrast to the traditional process in which water added to the raw materials to assist with blending had to be evaporated in the kiln. Cement plants can also reduce electricity use, a significant source of indirect GHG emissions resulting from fossil fuel combustion at the power plant providing the electricity.

Reducing calcination emissions is more vexing since they are inherent in the creation of CaO. One means of doing so is to make cement with a lower proportion of clinker, the intermediary product that results from the calcination process in the kiln. Product standards allow some diminution of clinker content in Portland cement, but there are limits to this solution.

Separation of the carbon dioxide from the kiln's waste stream is another possibility, though it is currently limited by the availability and cost of separation technologies. Gas separation technologies—such as the use of amine solutions—are expensive and energy intensive, potentially countering some or all of their benefits. These technologies also require a solution as to how to dispose of the resulting CO_2 gas without risking its ultimate release into the atmosphere.

New technologies that would permanently sequester CO_2, along with other pollutants, into a mineral form hold potentially greater promise. In this case, the resulting mineral product could potentially serve as an aggregate or cementitious material in concrete. If proven, these carbonate mineral sequestration technologies could enable cement manufacturers to capture their emissions and produce carbon-neutral cement and aggregate products to introduce into their distribution streams.

Concrete represents the other side of the climate change coin. As described earlier, concrete can create highly energy-efficient buildings and pavements. This can dramatically reduce overall GHG emissions as the users of these structures expend less energy on fuel and electricity over the course of their long lifetimes. In addition, carbonation can result in reabsorption of as much as half of the calcination emissions associated with the cement portion of concrete.

Cement is typically 10%–12% of concrete, with the bulk made up of sand and gravel (fine and coarse aggregates) and water. This reduces the carbon footprint by an order of magnitude compared to the cement itself. Obviously, any reduction to cement's carbon footprint also reduces that of concrete. The concrete industry also has the option of using a lower cement proportion, replacing it with SCMs such as fly ash and steel slag. The development of synthetic materials—either cementitious or aggregate—from carbonate mineral sequestration would hold great promise for concrete. If these materials were derived from sequestering emissions at a cement plant, they could result in carbon-neutral concrete, and if they were derived at a power plant or other CO_2 emission source, they could result in carbon-negative concrete.

2.4 ENVIRONMENTAL SUSTAINABILITY

The worldwide cement and concrete industries have adopted sustainability as a guiding principle. This commitment is evident in the industries' significant steps to reduce levels of air emissions, solid waste, and water discharges.

The global cement industry has been a shining case study for the effectiveness of voluntary measures. One example is the Greenhouse Gas Protocol developed in a cooperative effort by the World Resources Institute and the World Business Council for Sustainable Development (WBCSD), with active participation from the Portland Cement Association (PCA) and cement companies around the world. The protocol provides a consistent means of measuring CO_2 and other GHG emissions from cement plants.[2,4]

With a globally recognized and utilized measurement tool, the cement industry established voluntary CO_2 reduction goals. For example, PCA member companies committed to reduce their total CO_2 intensity by 10% between 1990 and 2020. Inspired by this pledge, many individual companies have set even more ambitious targets, whether unilaterally or through programs such as the World Wildlife Fund's "Climate Savers" or the US Environmental Protection Agency's "Climate Leaders."

As demonstrated elsewhere in this book, concrete can be the foundation of sustainable infrastructure, including applications in building and paving, due to its durability, thermal mass, rigidity, and other features. But concrete starts with a deficit balance in any sustainability assessment due to the environmental footprint of cement manufacturing.

Cement Case Study: India*

China is now the world's largest cement manufacturer, and India and other developing countries are rapidly increasing their production. Of course, these production increases also represent emission increases. The Indian cement industry is the second largest in the world with an installed capacity of more than 220 million t of cement in 2009. The industry is highly energy efficient; more than 95% of cement production comes from dry process technology. India has some of the world's best-performing plants in terms of lowest heat and power consumption. A general profile on the technological status of the industry is shown in Table 2.1.[5]

* This case study was authored by B. K. Modi of UltraTech Cement Limited, Mumbai, India.

TABLE 2.1
Technological Status of the Indian Cement Industry[a]

	Mini Vertical Shaft Kiln	Mini Rotary Kiln	Wet Process	Semidry	Dry	Grinding Units
Number of plants	193	17	26	4	107	29
Total capacity (million tonne)	1.51	3.11	5.71	1.80	146.56	20.3
Percentage of total capacity	0.84	1.73	3.18	1.00	81.87	11.34
Average kiln capacity (tonne/day)	30–75	200–800	150–900	600–1300	2400–10,000	600–2500[b]
Fuel consumption (kcal/kg of clinker)	850–1000	900–1000	1200–1400	900–1000	670–775	–
Power consumption (kWh/tonne of cement)	110–125	110–125	115–130	110–125	85–92	35–45[b]

Source: India: Greenhouse gas emissions 2007. Ministry of Environment and Forests, Government of India, May 2010.

[a] As of December 2007.

[b] Grinding capacity.

Driven by the urge to reduce cost in order to remain competitive in the market, the cement industry in India has focused on reducing energy costs from the current levels of 50%–60% of a plant's operating costs. Energy savings, of course, translate to GHG emission reductions.

The industry-wide exercise on profiling CO_2 emission was initiated by the Indian Ministry of Environment and Forests, and its second report was published in 2010. The report accounts for emission through 2007, during which the industry emitted a total of 129.92 million tonnes. That year, 56% of CO_2 emissions were from calcination and 44% from the combustion of fossil fuels.

India's largest cement producers are members of the WBCSD Cement Sustainability Initiative (CSI). They report their CO_2 emissions using CSI's CO_2 protocol. These members comprise roughly 45% of India's cement production. Many of them have pledged CO_2 emission intensity reduction in the short to long term ranging from 0.5% to 1% per annum. The CO_2 emission from some of the best plants in India is of the order of 0.5 tonne/tonne basis of cement. The efforts are mainly focused in the following directions:

- *Use of alternate raw materials*. The industry consumes around 30 million tonnes of fly ash and 8 million tonnes of slag annually to produce blended cement. In the process, it has cut CO_2 emissions by over 30% during the past decade (see Figure 2.1).

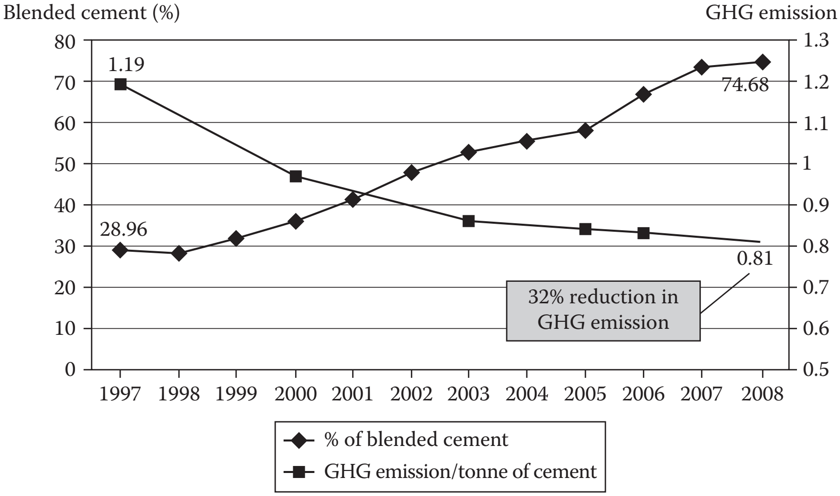

FIGURE 2.1 Blended cement percentage and reduction in GHG emission.

- *Technological upgrading*. Cutting energy consumption is at the core of the Indian cement industry's sustainability efforts. Energy-efficiency technologies include six-stage preheaters with precalciners, roller presses and closed-circuit grinding mills, waste heat recovery from flue gases, and the use of advanced control systems.
- *Alternative fuels*. During the last 5 years, the industry has advanced its utilization of waste fuels such as industrial wastes, municipal waste, and biomass as substitutes for fossil fuels. Some of the individual plants now consume more than 10% waste fuels based on total heat value. The industry has been working jointly with regulatory authorities in conducting the trials and formulating the relevant policies.
- *Regulatory requirements*. Recently, the government of India has tapped the cement and other energy-consuming industries for a focused energy reduction initiative. A regulatory body, the Bureau of Energy Efficiency, has been established to regulate energy consumption in these industries. The bureau is in the process of implementing a program called "Perform, Achieve and Trade" in which each plant will be given a challenging energy consumption target, and nonperformers will be required to pay penalties or buy energy certificates from performers.

The regulators have also announced a renewable power obligation requiring captive power generators and power distributors to derive a portion of their power from renewable sources. This renewable energy standard will scale up to 15% by 2020. Incidentally, the cement industry in India relies primarily on captive power for 70%–80% of its energy needs. Thus, the industry will be able to cut its emissions further by switching over to renewable power.[1]

2.5 REDUCING THE CEMENT COMPONENT OF CONCRETE

Since the most significant component of concrete's environmental footprint comes from the cement portion, one way to enhance the sustainability of concrete is to reduce the cement portion. Beyond Portland cement, there are a variety of materials that also react with water to form a solid mass. These SCMs can include natural minerals and industrial by-products such as fly ash and blast furnace slag. These materials can be added to Portland cement by the cement manufacturer and sold as blended cement. But SCMs are most commonly added to the concrete mix in place of a portion of the cement typically used. Cement typically comprises 10%–12% of the concrete mix. SCMs can replace up to half of this component but are more commonly used to supplant 10%–30% of the cement portion of concrete.

Reducing the cement component of concrete significantly reduces the environmental footprint of concrete as a building and paving material, allowing the post-construction benefits of sustainable building and pavements to weigh more heavily in sustainability assessments.

In addition to the SCMs mentioned above, there has been significant investigation into the development of replacements for Portland cement that have little or no environmental footprint. In some cases, these potential alternatives are actually derived from captured carbon dioxide emissions, so they could be said to have a negative carbon footprint. In other words, the formation of these products actually reduces the amount of carbon released into the atmosphere, whereas Portland cement manufacturing increases those emissions. With minimal or even beneficial environmental impact at the manufacturing stage, concrete could become by far the world's most sustainable building and paving material.

2.6 CHEMICAL ADMIXTURES

Chemical admixtures are used routinely in concrete. These trace portions of the overall mix serve such specific purposes as inhibiting corrosion, reducing the required water portion, and slowing or speeding the set time of the pour. Increasing the sophistication and application of chemical admixtures could enhance the sustainability of concrete. For example, a prospective product captures carbon dioxide emissions in a liquid form that enhance the performance of concrete and permanently embody the carbon in a carbonate form. A related discussion is presented in Appendix, with emphasis on regularly used chemical admixtures.

2.7 SOCIAL AND ECONOMIC SUSTAINABILITY

Social sustainability is a product of ensuring that employers, purchasers, and users of a product are not exposed to health and safety risks and that those products perform reliably, durably, and efficiently throughout their lifetimes. Many of the measures taken to achieve environmental and social sustainability directly benefit the financial bottom line and therefore contribute to economic sustainability. Air emissions, solid waste, and water discharges are the results of inefficiencies in an industrial system.

Greater energy efficiency, for example, improves both profits and the environment. Minimizing the wasting of cement kiln dust is another example.

A third example is the use of alternative fuels and raw materials. Using by-products of other industries saves the cost and environmental impact of mining or otherwise obtaining virgin raw materials. In many cases, cement plants are paid to utilize these materials. The most commonly used alternative raw materials include blast furnace and iron slag, fly ash, bottom ash, copper slag, foundry sand, mill scale, sandblast grit, synthetic gypsum, and waste glass. Commonly used alternative fuels include scrap tires, nonrecyclable plastics, waste oil, solvents, and other used and waste materials.

2.8 FUTURE OF CEMENT AND CONCRETE

Cement manufacturers around the world have taken great strides toward achieving well-balanced sustainability. While many industrialized countries strive to improve their environmental and social performance, there are other countries in which this is still not the case. India is an example of a country that is still grappling with significant development challenges yet one in which the cement industry is highly efficient and marked by many sustainable characteristics. Other developing countries should learn the lessons of the industrialized world and look to India as a model.

Even in the United States, Europe, and other countries with decades of government involvement in environmental improvement, the old command-and-control systems still dominate many facets of regulation. Further shifts in policy are necessary to support the holistic approach to controls that characterize an enlightened sustainability approach.

In addition, more research could further improve the sustainability of the cement industry. These efforts should include research into how to improve the manufacturing process and how to develop buildings and pavements that enhance user energy efficiency. Moreover, efforts to develop alternative cementitious materials that are much less environmentally detrimental—and perhaps are even environmentally beneficial—must move forward at a greater pace.

The world also needs to learn more about the effective use of cement and concrete to make stronger, more durable, and more energy-efficient structures. While such education can come from research into new techniques, simply spreading readily available knowledge could create great energy savings and therefore emission reductions. Greater and smarter use of concrete can offset the impact of cement manufacturing and help create a cleaner, safer, and healthier planet—the ultimate objective of sustainability.

2.9 CONCLUDING REMARKS

With the currently available technology, the application of concrete over its lifetime most enables the manufacturing emissions of the cement component to be negated. Because of concrete's greater thermal mass, concrete buildings provide natural insulation that can save energy associated with heating and cooling. Depending on location, concrete buildings use an estimated 44% less energy to heat and 32% less energy to cool than structures built with other materials. Concrete structures are also longer lasting and more durable and storm resistant, thus saving the energy associated with rebuilding.

Concrete pavements have lower rolling resistance, resulting in better gas mileage for vehicles. Several studies have indicated that trucks operating on concrete highways use between 0.8% and 6.9% less fuel, with higher differentials in warmer weather. These same principles would apply to automobile fuel efficiency but at lower rates due to the automobile's lighter weight. Since vehicle emissions represent roughly one-third of anthropogenic GHG emissions in the United States, a reduction of several percentage points would have significant impact on atmospheric concentrations.

Concrete as a pavement application uses far less energy for placement than other pavement materials do. Moreover, due to concrete's long life span, the energy used for repairs, maintenance, and replacement is drastically reduced, as well as the associated emissions.

Perhaps the most significant emission savings associated with concrete applications, however, is a function of its enhanced reflectivity in the context of urban heat islands. Since concrete is naturally lighter colored than other paving materials, it reflects light and reduces heat retention.

Studies conducted by the Environmental Protection Agency Cool Communities program have found that replacing dark- with light-paved surfaces can reduce urban summer temperatures by around 7°, dramatically reducing energy needs for every home and office building in the world's cities. These same properties can also help cities save on the cost of keeping streetlights lit at night.

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APPENDIX: CHEMICAL ADMIXTURES AND SUSTAINABILITY*

A.1 Role of Chemical Admixtures: Types and Functions

Unlike SCMs, chemical admixtures are nonpozzolanic, mostly organic, and physiochemical in their actions and are normally supplied as water-based solutions and suspensions, in powder form, and as dispersions and emulsions. These are mostly and conventionally added in amounts less than 5% by weight but have a profound impact on the performance of fresh and hardened properties of concrete. In the past, chemical admixtures were made from industrial by-products; the contemporary trend is

* This discussion is contributed by Dr. Chetan Hazaree, who is also the co-author of Chapters 6 and 15. His contribution is gratefully acknowledged.

shifting toward making chemical admixtures from synthetic polymers especially produced for the concrete industry.[1]

There are many types of chemical admixtures readily available in the market. With a rapidly evolving chemical admixture technology, it is difficult to offer a comprehensive classification system to cover all. Dodson's classification[2] of chemical admixtures based on the physiochemical mechanism that affects the fresh and hardened properties of concrete is quite simple and complete. He classifies the chemical admixtures into four categories:

1. Admixtures that disperse the cement particles in aqueous phase
2. Admixtures that alter the normal rate of hydration of cement phases, especially tricalcium silicate (C_3S)
3. Admixtures that interact with the by-products of hydrating cement
4. Admixtures that react neither with cement nor its hydrating by-products

Physically, the usage of admixtures alters the water demand, rheology of fresh concrete (stability, compactability, and mobility), quality and quantity of air, rate of cement hydration and resulting pore structure, and hence the consequent and associated properties. A detailed discussion is considered to be beyond the scope of the current discussion.

A.2 Environmental Impact of Concrete Admixtures

Figure A.1 shows the ecoprofile for superplasticizers in a concrete life cycle. This ecoprofile includes processes shown within the dotted line. Various aspects involved

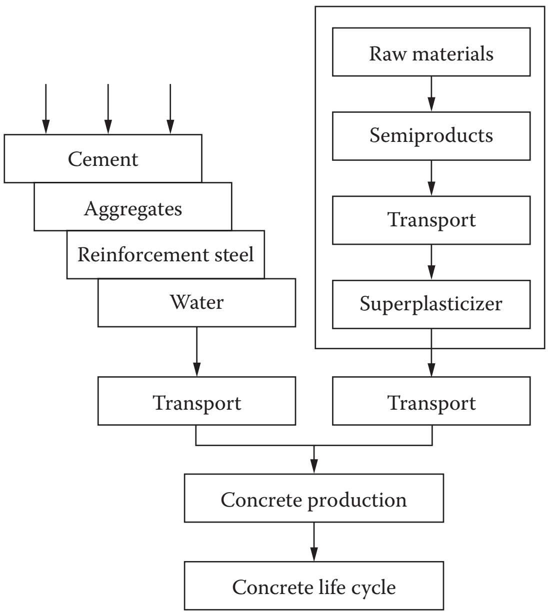


FIGURE A.1 Ecoprofile of superplasticizers in concrete life cycle. (From European Federation of Concrete Admixture Associations. Available at http://www.admixtures.org.uk, 2006.)

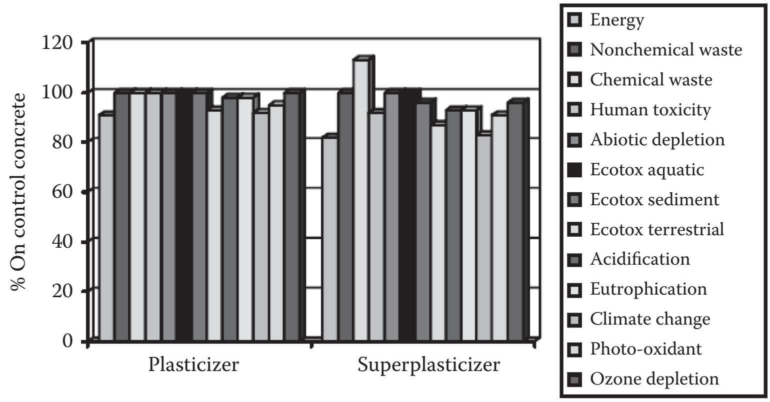
TABLE A.1
Ecoprofile for 1-kg Superplasticizers with 30%–45% Solids

Raw Materials: Input	Unit	Value
Coal, brown	g	82
Coal, hard	g	51
Crude oil	g	160
Natural gas	m^3	0.22
Emissions to Air		
CO_2	kg	0.72
CO	g	0.55
NO_x	g	1.8
SO_x	g	3.6
N_2O	g	0.067
Methane	g	1.2
Butane	mg	11
Pentane	mg	14
Methanol	mg	60
Ethene	mg	8.9
Benzene	mg	7.4
Nonmethane VOC	g	0.29
Polycyclic aromatic hydrocarbon (PAH)	µg	39
Acetic acid	mg	63
Ammonia	g	2.1
Arsenic (As)	µg	58
Chromium VI (Cr)	µg	16
Mercury (Hg)	µg	94
Nickel (Ni)	mg	0.46
Vanadium (V)	mg	1.2
Dioxins	ng	43
CFC-10	µg	2.0
CFC-114	µg	1.8
Halon-1211	µg	4.1
Halon-1301	µg	5.0
Emissions to Water		
Chemical oxygen demand	g	2.6
PAHs	µg	67
Oils, unspecified	g	0.63
Barite	mg	51
Nickel (Ni)	mg	3.9
Emissions to Soil		
Chromium VI (Cr)	mg	0.22
Oils, unspecified	g	0.66

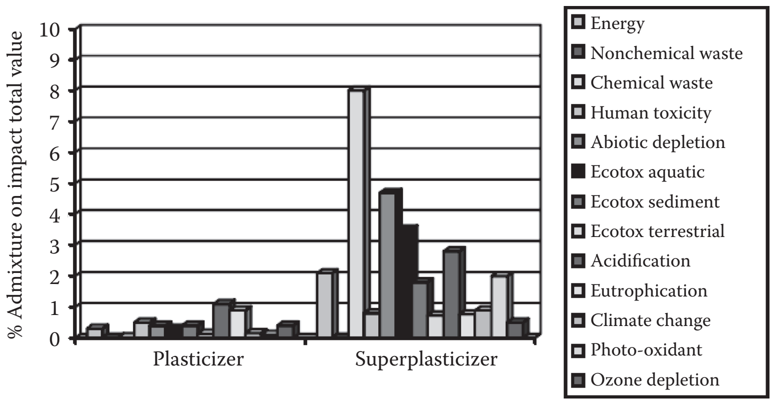
during procurement of raw materials, their processing, and production of final chemical admixtures are shown synoptically in this figure.

The environmental impact of chemical admixtures can be categorized based on the consumption of natural raw materials, consumption of energy, emissions, toxicity potential, risk potential, and land use. Table A.1 shows the ecoprofile details of superplasticizers, giving an account of the raw materials or ingredients and their carbon footprints.

The impact of use of chemical admixtures on waste generation can be considered in many ways. Figure A.2 shows one such analysis. It can be seen that the effect of the admixture is always small, but beneficial in reducing the total value of most impact categories, for which the contribution from the admixture is less than 1%. The typical and largest exception is the chemical waste from superplasticizer production of



Cement CEM I 52.5 Functional unit: precast wall unit



Cement CEM I 52.5 Functional unit: flat slab

FIGURE A.2 Relative impact of using chemical admixtures on the environmental impact. Figures are compared to control concrete, which was taken as 100%. R: percentage contribution to each of the impact categories. (From Dransfield, J. Cement Admixtures Association. Available at http://www.admixtures.org.uk, 2006.)

about 8%. However, as previously noted, the actual value of this waste is very small because the whole concrete production process produces little chemical waste.[3]

A.3 Economic Impact of Chemical Admixtures

Although individual benefits of each of the admixtures can be listed in terms of their materials' cost saving, process cost saving, and long-term durability, the key property to appreciate is the low carbon footprint that admixtures offer to concrete. The quantity of admixture added is much less than the benefits that it offers in terms of enhancing the sustainability of concrete.

Admixtures are mainly organic chemicals and therefore have inherently highly embedded carbon dioxide (ECO_2) content; the amount depends on admixture type (typically, 80 kg/tonne for retarders, 220 kg/tonne for plasticizers, and 760 kg/tonne for superplasticizers). However, the quantity of admixture added to concrete is small—rarely more than 0.3% on concrete weight and more typically less than half this quantity. Thus, according to the ISO 14000 series of standards and Building Research Establishment guidance, the contribution to embedded carbon from admixtures at less than 1% is too small to be significant and can be ignored when calculating the ECO_2 of the concrete. Against this, the environmental benefits from admixture use can be significant because they allow other high-carbon components of concrete to be reduced without affecting the concrete properties. Based on published ECO_2 figures for other concrete constituents, it is estimated that current admixture use already saves about 600,000 tonne of ECO_2 per annum, and this could be significantly increased by further mix optimization.[4]

A.4 Challenges in Chemical Admixture Technology and Concrete

The growing challenges to concrete and concreting practice translate to concrete science and chemical admixture technology as well. A few are listed here:

- Understanding of mechanisms through which chemical admixtures interact with binder systems, including the rate of their consumption and what happens to the residual admixture
- Compatibility of chemical admixtures with different cements and binder systems
- Mutual compatibility of two or more chemical admixtures when used in a concrete mixture
- Pushing the lower limit of water/binder ratio for producing workable concrete
- Tailoring chemical admixtures to act synergistically with the concrete placing techniques
- Reducing human involvement in concrete making and concreting

As stated before, concrete is used in a wide range of applications, from housing to various infrastructures. The challenges for concrete as a material and in concreting methodology are ever expanding. The admixtures for regular concrete pavement construction are routinely used retarders and air-entraining agents. On the other hand, for self-consolidating concrete, the routinely used admixtures are high-range water reducers, powerful workability retaining agents, rheology modifiers, and air-entraining agents. Each of these concrete systems poses different types of challenges that cannot be regularly met with already existing families of products. In large infrastructure construction projects, it is customary to tailor admixtures according to the project requirements.

Housing needs are increasing in developing countries like India. The number of multistory buildings is increasing in megacities. These demand high-strength and high-performance concrete that often requires detailed infestation of concrete's performance characteristics to fulfill the material constants taken into account during the design stage. Pumping of concretes to increasing heights presents challenges to concrete mixture proportioning—not just for retaining the required workability but also for volumetric stability during setting and hardening.

Shrinking project times have forced engineers to think the "lean" route. This means not only the concrete cost but also the cycle time for producing or fabricating a product or structure has to be reduced. Another example is that of reducing the prestressing time of concrete for bridge girders from 7 to 3 days, implying that the strength is to be achieved in 3 days instead of 7 days.

Depletion of natural resources for concrete making is posing another challenge. The admixture chemistry suitable for making new concrete from virgin materials might not be suitable for concretes incorporating recycled concrete aggregates. Achieving the right properties for fresh and hardened concrete while ensuring adequate durability is another challenge.

In addition, these changes in the cementitious materials are also leading to complications in terms of admixture usage. The use of fly ash, slag, and silica fume is widely accepted in practice. Moreover, the trend is also increasing in terms of using ternary and quaternary blends of binders for enhancing the overall performance of concrete. Research is also under way for finding alternatives to ordinary Portland cement.

In summary, the chemical admixtures have become an essential component of modern concrete due to their ability to satisfy enhanced material requirements and for better concrete and cementing. The use of combinations of SCMs in conjunction with the ordinary Portland cement is posing challenges in terms of tailoring the chemistries to alter the concrete behavior adequately. The search for higher strength and higher performance is driving the development of newer combinations of materials. All these factors combined together are leading to the development of newer and more powerful admixtures.

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3 Principles of Sustainable Building Design

Subramanian Narayanan

CONTENTS

3.1 INTRODUCTION

Our planet earth is in peril due to severe climatic changes. A growing population coupled with urbanization has resulted in unprecedented problems for our cities. Unless we take urgent measures, these problems will result in catastrophic consequences. The increase in population with ever-increasing demands for energy has resulted in energy crises all over the world. The current use of fossil fuels, which may be depleted in another 40–50 years, has resulted in the release of huge amounts of greenhouse gases (GHGs), especially carbon dioxide, which is harmful to the environment. The unmindful use of resources has also resulted in huge amounts of waste products, and we have developed only a few reliable and safe methods to dispose of or recycle them. Landfills in many countries are overflowing, resulting in many pollution problems.

Water, which is considered plentiful, is also becoming scarce due to climatic changes, and many regions in the world are fighting for their share of water resources. This is compounded by the unmindful paving of roads, platforms, and areas around buildings by impermeable pavements, resulting in runoff and flooding of precious rainwater. Though strict rainwater harvesting measures have been implemented by a few governments, these measures have some drawbacks. Pervious concrete pavements offer an attractive solution to water runoff and associated water pollution problems.

The built environment contributes significantly to global raw material use, energy use, solid-waste generation, and GHG emissions. Hence, to promote design and construction practices, which reduce the negative environmental impacts of buildings and improve occupant health and well-being, the US Green Building Council (USGBC; a nonprofit coalition of building industry leaders based in Washington, DC) developed the Leadership in Energy and Environmental Design (LEED) green building rating system. In the United States and in a number of other countries around the world, LEED certification is the recognized standard for measuring building sustainability.

In addition, every major city within the United States is burdened by abandoned manufacturing facilities and industrial sites, known as *brownfields*. These brownfields threaten the environment around them, and the US Environmental Protection Agency (EPA) has developed programs to promote restoration and reuse of such contaminated lands. Recently the EPA, along with the Federal Highway Administration (FHA) and an extensive network of environmental, industrial, and governmental collaborators, developed the Green Highway Partnership (GHP). The aim of the GHP is to ensure that sustainability becomes the driving force behind infrastructure development. A green highway integrates transportation functionality and ecological sustainability.

This chapter discusses the features of sustainable development and provides some case studies of projects that have been executed to maintain sustainability of our shrinking resources.

3.1.1 Definition of Sustainability

Though several definitions for sustainability are available, that suggested by then Prime Minister of Norway, Gro Brundtland, in 1987—*meeting the needs of the present without compromising the ability of future generations to meet their needs*—is considered simple and effective.[1] Sustainable development or, simply, sustainability is thus a realization that today's population is merely borrowing resources and environmental conditions from future generations.

3.2 ENVIRONMENTAL THREATS

The greatest threats to the sustainable development on earth are population growth and urbanization; energy use and global warming; excessive waste generation and the subsequent pollution of soil, air, and water; transportation in cities; and a limited supply of resources. Let us now briefly discuss these threats. Many of them are interrelated.

3.2.1 Population Growth

The world population in 2014 was estimated at 7.25 billion with an annual growth rate of about 1.14%. To put the recent growth in perspective, the world population in the year 1900 was only 1.6 billion, and in 1960, it was 3.0 billion. According to the United Nations (UN), the world population is expected to reach 8 billion people in the spring of 2024 and 10 billion in 2062 (see Figure 3.1).

Currently, 80 million people are being added every year in less developed countries, compared with about 1.6 million in more developed countries (see Figure 3.2). By 2030, India is expected to surpass China's population to become the most populated country in the world. Thus, populations are growing more rapidly in places that cannot afford such growth.

Ecological footprint analysis is widely used around the globe as an indicator of environmental sustainability.[2] Ecological footprint analysis compares human demand on nature with the biosphere's ability to regenerate resources and provide services. This approach can also be applied to an activity such as the manufacturing of a product or driving of a car. This resource accounting is similar to life cycle analysis (LCA), wherein the consumption of energy, biomass (food, fiber), building materials, water, and other resources is converted into a normalized measure of land

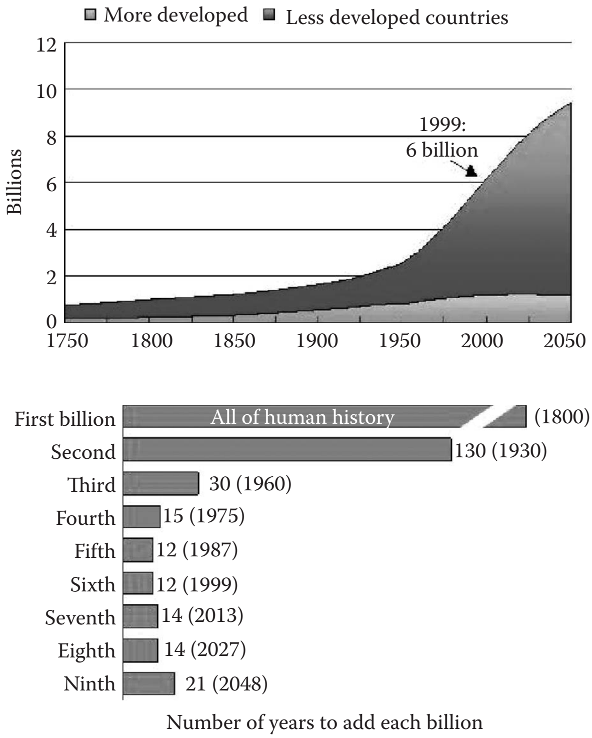


FIGURE 3.1 Population trend from 1750 to 2050. (From http://www.sustainablescale.org.)

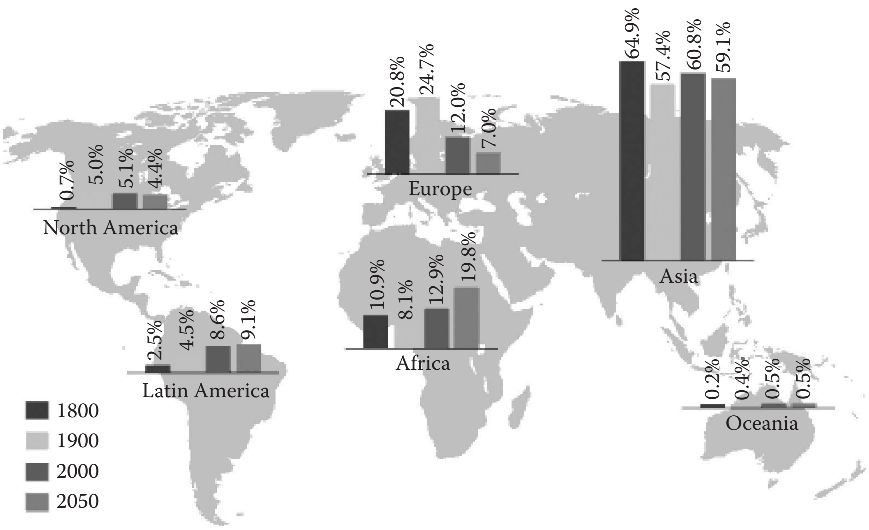


FIGURE 3.2 Distribution of world population. (From http://www.prb.org.)

area called "global hectares" (gha).* A hectare is a unit of area equal to 10,000 m^2 (107,639 ft^2).

3.2.1.1 Some Interesting Statistics

The amount of *bioproductive land* and sea available to supply human needs is limited. It is estimated that only one-eighth of the earth's surface is suitable for humans to live on; three-quarters is covered by oceans, and half of the land area is desert (14%), high mountains (27%), or other less suitable terrain.

Currently, approximately 13.6 billion ha of productive earth, divided by 7.18 billion people who depend on it for their well-being, results in an average of approximately 1.89 gha/person. Collectively, we are currently using approximately 2.7 gha/person—over 42% more than what is produced annually; this means that the population has already exceeded the sustainable limit. The ecological footprint for the United States is 9.02 gha/person against its biocapacity of 5 gha (http://www.footprintnetwork.org).

According to the US Census Bureau estimates, the population in the United States was about 318.55 million in 2014. The country has a total fertility rate (TFR) of 2.01, high for an industrialized country. The US population is expected to be 438 million by 2050. Taiwan has the world's lowest TFR of 1.11 children per woman, while Japan and South Korea have TFRs of 1.4 and 1.25, respectively (http://www.cia.gov). CNN.com reports that at least one employer in Japan, Canon, is letting its employees leave work early two times a week to "go home and multiply." The population density in Tokyo is 6029 persons per square kilometer, compared to the national average of 337 persons per square kilometer in 2012.

3.2.2 Urbanization

According to the UN World Urbanization Prospects Report (2007, pp. 7–16), the twentieth century is witnessing "the rapid urbanization of the world's population." The global proportion of urban population rose dramatically from 29% (736 million) in 1950 to 53% (3.8 billion) in 2013.[3] The same report projects that about 60% (4.96 billion) of the global population is expected to live in cities by 2030 (see Figure 3.3). The percentage of urban population of India increased from 17.0 in 1950 to 32 in 2013 and that of the United States from 64.2 to 83. In 1950, there were only two megacities with 10 million or more inhabitants. The number of megacities increased to 5 in 1975 and 28 in 2014 and is expected to increase to 41 in 2030. Out of the 28 megacities, 16 are located in Asia, 4 in Latin America, 3 each in Africa and Europe, and 2 in Northern America. It is projected that Asia and Africa will have more urban dwellers than any other continent of the world, and Asia will contain 54% of the world's urban population by 2030. Tokyo remains the world's largest city with 38 million inhabitants, followed by Delhi with 25 million; Shanghai with

* Global hectare is a measurement of biocapacity of the entire Earth; one global hectare is a measurement of the average biocapacity of all hectare measurements of any biologically productive area on the planet. It is the sum of the world's biocapacity divided by the number of hectares on the Earth's surface. The term "global hectare per person" refers to the amount of biologically productive land and water available per person on the planet.

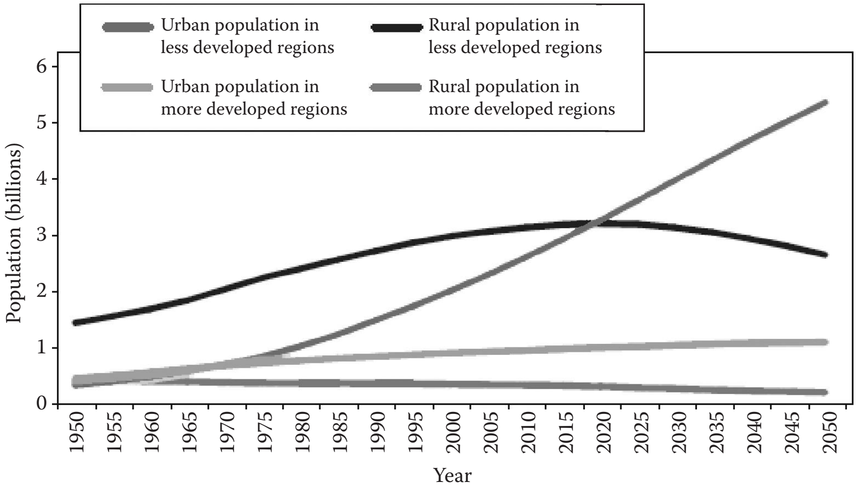


FIGURE 3.3 Urban and rural population growth of the world, 1950–2050. (From United Nations, Department of Economic and Social Affairs, Population Division 2007.)

23 million; and Mexico City, Mumbai, and São Paulo, each with around 21 million inhabitants.

Population growth coupled with urbanization results in significant impacts on the environment and other problems, which include the following[4]:

- Increased ambient temperature
- Decreased air quality
- Increased water runoff
- Decreased quality of runoff water
- Altered weather patterns
- Loss of aesthetic beauty or character/the community
- Reduction in farm lands and subsequent food shortage
- Deforestation (occurring at a rapid rate, with 0.8 ha of rain forest disappearing every second, and linked to negative environmental consequences such as biodiversity loss, global warming, soil erosion, and desertification)

Urbanization also results in the migration of rural populations to towns, resulting in increased development of slums; increased pollution and waste; and the need to develop infrastructure for housing the masses, educational facilities, roads and highways, health care, civil supplies, etc. Congestion of living space, inadequate lung space, and traffic result in increases in diseases.

In addition, population growth and urbanization pose significant challenges for water resources management throughout the world. Urban populations consume much more food, energy, and durable goods than rural populations do. The urbanization of the world's populations will increase aggregate energy use. Urban areas not only generate more rain but also reduce the infiltration of water and lower the water tables. This means that runoff occurs more quickly with greater peak flows. Flood volumes increase as do floods and water pollution downstream.

3.2.3 Energy Use and Global Warming[4–7]

According to the US Department of Energy (DOE), in 2013, the average total worldwide power consumption of the human race was 18.3 TWyr (=18.3 × 8.76 × 10^{12} kWh or = 18.3 × 29.89 quad) with 86.5% from burning fossil fuels (oil, coal, and natural gas). Figure 3.4 shows that there is a broad relation between wealth and energy consumption. Figure 3.5 shows the contribution of various sources to this worldwide power consumption.[8] The energy consumption in India rose threefold, from 4.16 to 12.8 quadrillion Btu between 1980 and 2001, putting India behind only the United States, Germany, Japan, and China in total energy consumption. According to the International Energy Outlook projections for 2030 of the US DOE, China and India account for nearly one-half of the total increase in residential energy use in non-Organization for Economic Cooperation and Development countries. However, the per capita consumption of power in India during 2011 as calculated by the Central Electricity Authority was about 684 kWh only, as compared with the per capita consumption of 13,246 kWh in the United States.

Though the greenhouse effect occurs naturally (providing a habitable climate), atmospheric concentrations of some of the gases that produce the greenhouse effect are increasing due to human activity causing global warming. Over one-third of

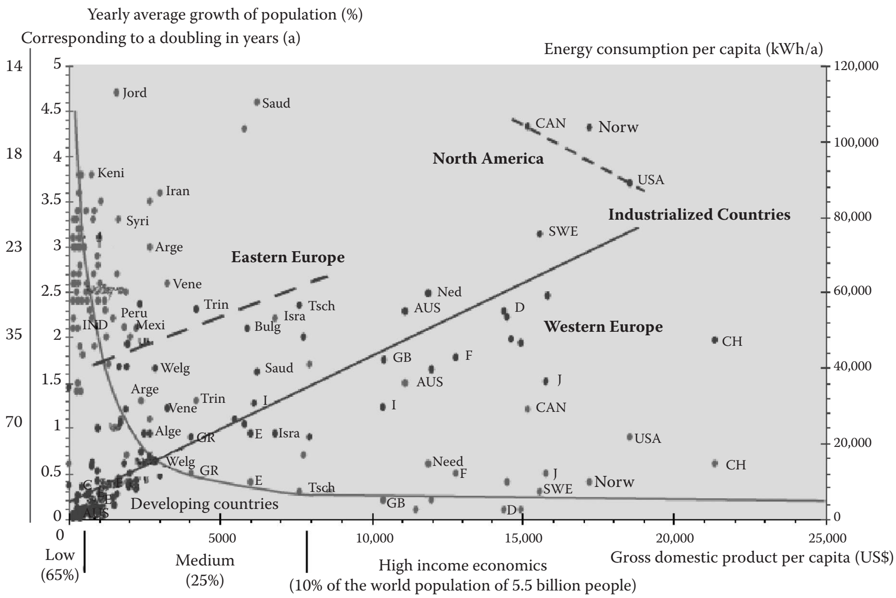


FIGURE 3.4 Correlation between per capita energy consumption, per capita Gross National Product and population. (From http://www.sbp.de/de/html/projects/solar/aufwind/index.htm. With permission.)

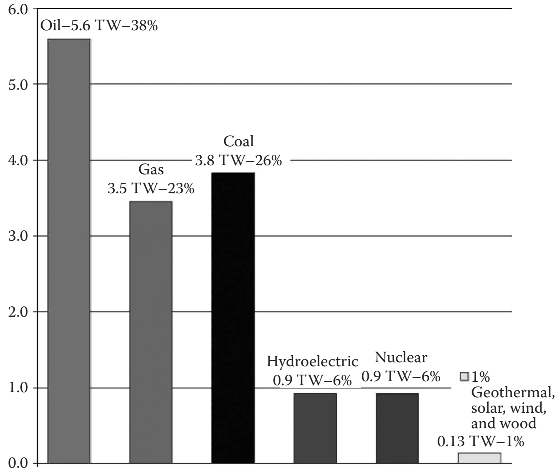


FIGURE 3.5 Worldwide energy supply in terrawatts. (From Energy Information Administration. Official Energy Statistics from the US government. Available at http://www.eia.doe.gov/emeu/consumption/.)

human-induced GHGs come from the burning of fossil fuels to generate electricity. All fossil fuels are made up of hydrocarbons and release carbon dioxide when burned.

The principal GHGs that enter the atmosphere because of human activities are the following:

- *Carbon dioxide (CO_2).* Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, and trees and wood products, as well as a result of other chemical reactions (e.g., manufacture of cement). About half of the CO_2 that enters the atmosphere is removed by nature by dissolving it in seawater at the surface of seas (called carbon sink). This makes the sea water acidic. Carbon dioxide is also removed from the atmosphere (or "sequestered") when it is absorbed by plants as part of the biological carbon cycle. When Charles Keeling of the National Oceanic and Atmospheric Administration (NOAA) started measuring CO_2 in the atmosphere in 1959, the level was 316 ppm. In July 2014, that level has reached an alarming level of 401.3 ppm, as shown in the Keeling curve in Figure 3.6.
- *Methane (CH_4).* Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid-waste landfills. Current atmospheric concentration of methane is about 1800 ppm.
- *Nitrous oxide (N_2O).* Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste. Current atmospheric concentration of nitrous oxide is about 325 ppm.

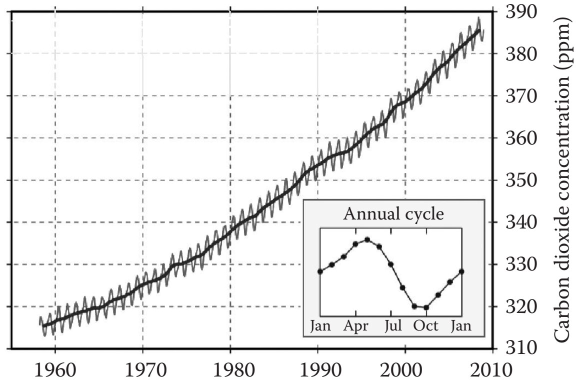


FIGURE 3.6 Atmospheric carbon dioxide, measured at Mauna Loa, Hawaii. (From NOAA.)

- *Fluorinated gases*. Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic, powerful GHGs that are emitted from a variety of industrial processes. These gases are typically emitted in smaller quantities, but because they are potent GHGs, they are sometimes referred to as high global warming potential gases.

It is interesting to note that The Associated Cement Companies (ACC) Limited (India's foremost manufacturer of cement and ready-mix concrete, with 14 cement factories) has initiated a project to sequester CO_2 generated by their kilns to produce high-energy, oil-bearing algal biomass, which can then be reused as fuel in cement kilns. Such projects call for a multidisciplinary approach and involve microbiologists, algae experts, biotechnologists, engineers, and other professionals.

In addition to the gases mentioned, volatile organic compounds, radon, asbestos, carbon monoxide, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and combustion particulates may affect indoor air quality (IAQ). These are introduced into the indoor environment by painting, glues, solvents, wood preservatives, installation of carpets, or cleaning products. It has to be noted that asbestos products are not yet banned in India. Sector-wise global GHG emissions are shown in Figure 3.7. It is seen that the two large contributions are due to burning coal to produce electricity and burning petroleum products to run vehicles.

Though nuclear power plants do not emit GHGs, no solution has yet been found to the safe disposal of plutonium and other wastes from nuclear power plants, which are highly radioactive. Note that plutonium takes approximately 25,000 years to decay to half of its original potency. (For example, in the past 50 years, the United States has accumulated about 30,000 t of spent fuel rods from power reactors and another 380,000 m^3 of high-level radioactive waste, a by-product of producing plutonium for nuclear weapons. None of these materials has found anything more than interim accommodation.)

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5-2014) of the UN predicts that, based on a range of scenarios, by the end

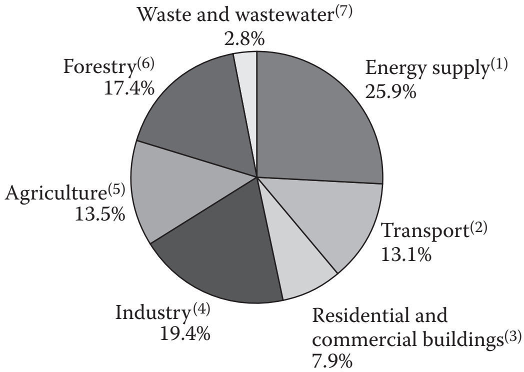


FIGURE 3.7 Global GHG emissions in 2004 from different sectors. (From Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.3 (c). IPCC, Geneva, Switzerland. With permission.)

of the twenty-first century, climate change (due to the emission of GHGs) will result in the following:

- Further warming will continue if emissions of GHGs continue.
- The global surface temperature increase by the end of the twenty-first century is likely to exceed 1.5°C relative to the 1850 to 1900 period for most scenarios and is likely to exceed 2.0°C for many scenarios.
- The global water cycle will change, with increases in disparity between wet and dry regions, as well as wet and dry seasons, with some regional exceptions.
- Global mean sea level will continue to rise at a rate very likely to exceed that of the past four decades.
- The oceans will continue to warm, with heat extending to the deep ocean, affecting circulation patterns.
- Decreases are very likely in Arctic sea ice cover, Northern Hemisphere spring snow cover, and global glacier volume.
- Changes in climate will cause an increase in the rate of CO_2 production. Increased uptake by the oceans will increase the acidification of the oceans.
- Future surface temperatures will be largely determined by cumulative CO_2, which means climate change will continue even if CO_2 emissions are stopped.

It is interesting to note that the IPCC and former US Vice President Al Gore were awarded the Nobel Peace Prize for the year 2007 for their efforts to build up and disseminate greater knowledge about man-made climate changes and to lay the foundations for the measures that are needed to counteract such change. It is reported that the global cost of climate-related disasters has doubled every decade, from $50 billion in the 1960s (16 disasters) to $400 billion in the 1990s (70 disasters) and to $139 billion in 2012 alone.

According to new NASA satellite data, the Arctic Ocean could be nearly free of ice in a couple of years—much faster than the previous predictions had indicated. (Arctic sea ice is declining by nearly 4% per decade.) Faster melting there means eventual sea level rise and more immediate changes in winter weather because of less sea ice. White sea ice reflects about 80% of the sun's heat off earth. When there is no sea ice, approximately 90% of the heat goes into the ocean, which then warms everything else. Warmer oceans then lead to more melting.

The objective of the Kyoto Protocol, which was implemented in February 2005, is to reduce the emissions of carbon dioxide and five other GHGs (5% below their 1990 level) or to engage in emissions trading if emissions of these gases are maintained or increased. As of November 2007, 174 countries had ratified the protocol, with the exception of the United States and Kazakhstan. There was a lack of binding commitment or an extension of the Kyoto commitment period in climate talks at the Conference of Parties (COP 15) in Copenhagen, Denmark, in 2009. Further rounds of negotiations (COP 16) were discussed at the UN Climatic Change Conference at Cancun, Mexico, in December 2010, but no major progress was made. Governments are in the process of negotiating a new universal climate change agreement, which is set to be adopted in Paris in 2015 and enter into effect in 2020.

Though there may be some differences of opinion about the development of global warming, all agree that there is a depletion of resources, such as metals, fossil fuels, and nonrenewable energy sources. Hence, it is important to give serious consideration to replacing these resources in construction in order to use existing reserves over a long period.

Cement production is one of the most energy-intensive industrial processes in the world. In many countries of the world, energy cost is about 50%–60% of the direct production cost of cement. Energy is required for the thermal heating of the kiln, calcination, and drying processes as well as for operation of motors for grinding mills, fans, conveyers, and other motor-driven process equipment. Thermal energy accounts for approximately 20%–25% of the cement production cost.[9] The typical electrical energy consumption of a modern cement plant is about 110–120 kWh/tonne of cement.[9] In dry process cement plants, nearly 40% of total heat input is rejected as waste heat from exit gases of preheaters and grate coolers.

The world demand for cement was 3730 million tonnes (MT) in 2012, and China accounted for about 58% of the total demand. It is predicted that the demand will be about 4193 MT in the year 2015. In a typical cement industry, approximately 29% of the expense is spent on energy, 27% on raw materials, 32% on labor, and 12% on depreciation.[9] Specific thermal energy consumption in cement industries is found to be about 4 and 5 GJ/tonne.[9]

The Kalina cycle® (invented by the Russian engineer Alexander I. Kalina in the mid-1980s as an alternative to the conventional Rankine cycle) utilizes the waste heat from the cement production process to generate electrical energy with no additional fuel consumption and reduces the cost of electric energy for cement production. The thermal efficiency improvement of the Kalina cycle is 20%–40% in comparison with conventional waste heat power plants that utilize the hot gases available in a cement plant. A Kalina cycle power plant offers the best environmentally friendly alternative for power generation from low-grade waste heat. It maximizes kilowatt hours generated using a closed loop system to recover heat for electricity production without hazard to the environment.[10]

The Kalina cycle uses a mixture of ammonia and water as its working fluid—a common solution used extensively worldwide for refrigeration plants. In the event of an accidental release, ammonia is considered a biodegradable fluid. It does not contribute to photochemical smog, global pollution, or global warming and will not deplete the ozone layer. Its use as an industrial fluid is well documented, and it has a proven track record for safety in industrial plants.[10] Cement plants in several countries have implemented such waste-heat recovery systems. In many plants, waste heat is also used for drying raw material or preheating air required for coal combustion. The energy use at different sections of cement industries, specific energy consumption, types of energy use, details of cement manufacturing processes, and various energy savings measures are reviewed in Ref. 9.

3.2.4 Water Shortage and Scarcity

About 97.5% of water on the earth is saltwater; this leaves only 2.5% as freshwater, of which over two-thirds is frozen in glaciers and polar ice caps. (These are also melting at a faster rate due to climatic change. Scientists have predicted that the North Pole may soon be ice free.) The remaining unfrozen freshwater is mainly found as groundwater, with only a small fraction present above ground or in the air.[11] Freshwater is a renewable resource, yet the world's supply of clean freshwater is steadily decreasing.

The population is not only growing but also using more water even though the world's total supply remains the same. Since 1900, the world population has *doubled*, yet the amount of freshwater used has increased more than *sixfold*. Agriculture is by far the largest consumer of water, mostly because of the expansion of irrigated areas nearly fivefold over this century. Nearly 70% of global water withdrawals from rivers, lakes, and aquifers are used for irrigation, while industry and households account for 20% and 10%, respectively. (More efficient irrigation techniques are clearly the first and crucial step to reducing water use. It may also be noted that, of late, the world's irrigated areas are growing more slowly than the population. Per capita irrigated areas peaked in 1978 at 0.48 ha/person. Since then, this has fallen 6%. Worsening shortages of freshwater along with rising costs of irrigation are placing global food supplies in jeopardy, according to a new study from the Worldwatch Institute, a research organization in Washington, DC. Although the use of drip irrigation has grown more than 50-fold over the last 20 years, it is still used in only 1% of the world's irrigated areas.) This scarcity could put a major brake on most of the world's development efforts.

Assessments of global water resources indicate that water scarcity will increase dramatically during the next decades, with a disproportionate and severe effect on developing countries. Demand is growing and, with it, competition among different users. Unless we change the way we think about and manage our water resources, both people and the planet could suffer irreparable damage.[12] The UN Educational, Scientific and Cultural Organization predicts that many countries will still face "physical water scarcity in 2025" and that their water needs will outstrip supplies, no matter what measures are taken. Others will be faced with "economic water scarcity": They will lack the financial and institutional capacity required to increase their water supplies by 25% (see Figure 3.8).[11] Pressure on water resources is particularly acute in arid regions that support agricultural production or large populations—regions where water use is high relative to water availability. The Middle East, Central Asia, North Africa, South Asia, China, Australia, the western United States, and Mexico are especially prone to water shortages (see Figure 3.8).

Global per capita water availability decreased from 13,000 m^3 in 1970 to 6800 m^3 in 2004. An optimistic calculation shows that, assuming current trends, only 4800 m^3 will be available in 2025. When per capita water supply is less than 1700 m^3/year, an area may be considered as *water stressed*.[13] In many parts of the world, water supply is actually less than 1000 m^3/capita, which causes serious problems for food production and economic development. Today, 2.3 billion people live in water-stressed areas.[11] If current trends continue, water stress will affect 3.5 billion people—about 48% of the world's projected population in 2025.[11] Existing problems of water scarcity are aggravated by water pollution. In many parts of the world, rivers and lakes have become so polluted that their water is unfit even for industrial uses. Global concerns about water scarcity include not only surface water sources but also groundwater sources.

In the United States and Europe, between 200 and 600 L of water per day are used by individuals, compared to the 20 L deemed to be the minimum daily requirement for drinking, washing, cooking, and sanitation.[13] Such unsustainable consumption levels have led to localized areas of water scarcity and significantly altered freshwater ecosystems. The massive Colorado River in the United States, which runs

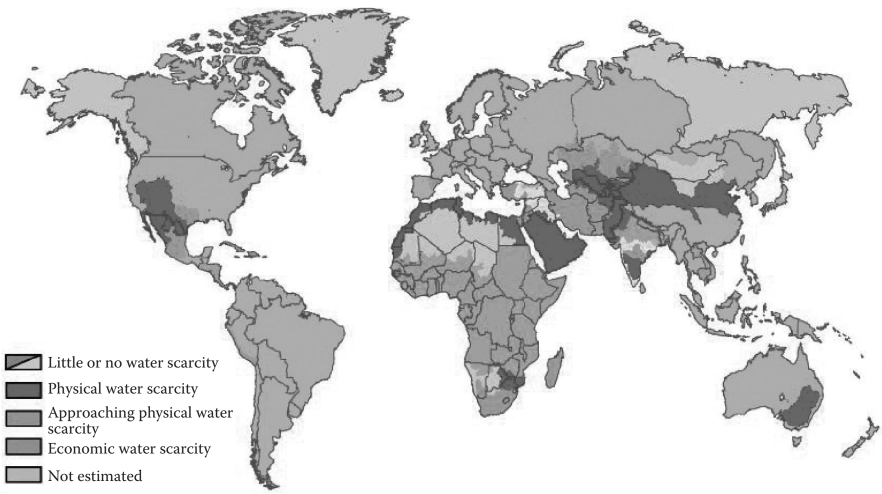


FIGURE 3.8 Areas of physical and economic water scarcity. (From IMWI Report, Insights from the Comprehensive Assessment of Water Management in Agriculture, 2006. With permission.)

through the cities of Los Angeles, San Diego, and Las Vegas and feeds millions of agricultural fields, now runs dry before reaching the ocean. Due to this, the Colorado River Delta, which once supported plentiful plant and animal life, is now significantly diminished.[13] *Though India has about 16% of the world's population, it has only 4% of average annual runoff in rivers.*[13] In almost all parts of India, water deficiencies show an increasing trend, and the surpluses show a decreasing trend. Water availability is estimated at 972 m^3/person/year. One-third of India is always under the threat of drought, and many states have serious river water-sharing disputes with neighboring states, which are going to grow in the future.

Population growth and urbanization pose significant challenges for water resource management throughout the world. Urbanization increases surface runoff (storm-water runoff occurs when rain falls) due to more impervious surfaces, such as pavements and buildings. These surfaces do not allow percolation of the water down through the soil to the aquifer, and thus the result is lower water tables. It has recently been reported that, in Mexico City, some reservoirs dropped to their lowest levels in 16 years, which made the government shut down water pipelines to more than 2 million residents under a new conservation program.

Unlike rural roads, urban roads are paved with asphalt or concrete, which seldom provides percolation of rainwater. Moreover, the platforms of these roads are also covered with concrete slabs. The latest trend is to cover most of the areas around dwellings with concrete interlocking blocks since they may add visual appeal to a building. This means that runoff occurs more quickly in urban areas with greater peak flows. Flood volumes increase, as do floods and water pollution downstream. A few cities in India (e.g., Chennai) imposed compulsory *rainwater harvesting systems* for individual house owners. Note that such systems have to be maintained properly in order to be successful in the long run. A recent study by Chennai Metrowater showed that there has been a 50% rise in water level in the last 5 years, and the water quality has significantly improved.

Water runoff from pavements and terraces of buildings often creates *erosion* and *siltation* problems, as well as causes flash floods and loss of rainwater that could otherwise replenish water tables and aquifers. (A land area producing runoff draining to common point is called a *watershed* and is critical to environmental, financial, and social health.) When runoff flows along the ground, it can pick up soil contaminants such as petroleum, pesticides (in particular, herbicides and insecticides), or fertilizers, which may be dissolved or suspended in runoff. This pollutant load can reach various receiving waters such as streams, rivers, lakes, estuaries, and oceans polluting these water systems and their related ecosystems. (In a study of groundwater wells in agricultural southwestern Ontario, Canada, 35% of the wells tested positive for pesticides on at least one occasion.[14] Similar observations have been made in the United States and other countries.) In rivers, streams, lakes, and bays, fertilizers contribute to algal blooms and excessive plant growth and can lead to eutrophication. Pesticides and herbicides can be harmful to human and aquatic life.

In the past, engineers have dealt with issues connected with water runoff by designing gutters, permanent storm-water retention/detention ponds, slope protection, or grass strips and by providing temporary sediment traps, silt fences, and diversion trenches. All of these methods may help reduce runoff pollution. Lately, a different approach to the challenge has been gaining attention: Do not let the water run off. This approach has resulted in the development of *pervious concrete* pavements.[15–18] (See Chapter 5 of this book/volume for the details of pervious concrete.)

3.2.5 Waste Management

Waste management is the collection, transport, processing, recycling, or disposal of waste materials. Waste management usually relates to materials produced by human activity and is generally undertaken to reduce their effect on health, aesthetics, or amenity. Waste management is also carried out to reduce the materials' effect on the environment and to recover resources from them; it involves solid, liquid, or gaseous substances, with different methods and fields of expertise for each (see Figure 3.9).[19] Various methods are used for waste management, including disposal (landfill and incineration), recycling (physical and biological processing), energy recovery, and avoidance and reduction (see Figure 3.10).

According to ASCE, the United States generated 250 million tonnes of municipal solid waste (MSW) in 2010, which is approximately 2.1 kg of waste per person per day. More than one-third was reported to be recycled or recovered, representing an increase of 7% since 2000. Per capita generation of waste has remained constant over the past 20 years. Waste disposal statistics do not take into account waste that is disposed (burned or put in landfills) on-site or off-site in unpermitted landfills and incinerators. Despite this, the increasing volume of electronic waste and the lack of uniform regulations for disposal create the possibility for high levels of hazardous waste and heavy metals to be dumped in landfills, posing a significant threat to public safety.

The Central Pollution Control Board in India estimates the current quantum of MSW generation in India to be to the tune of 48 million tonnes/annum, of which the

FIGURE 3.9 Waste management can involve solid, liquid, or gaseous substances. (From Campioli, A., and M. Lavagna, *Third International Conference on Life Cycle Management*, Zurich, August 27–29, 2007.)

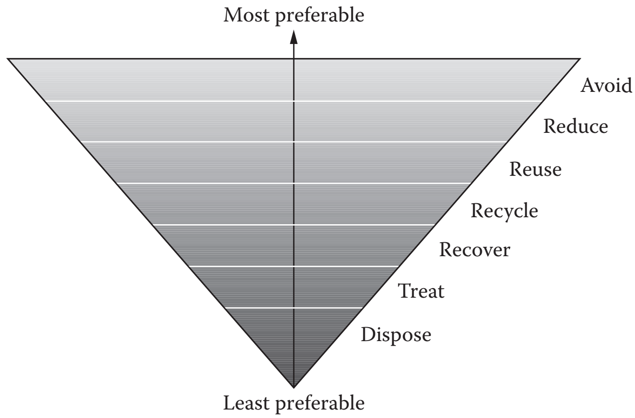


FIGURE 3.10 Hierarchy of waste management. (From http://www.envirocentre.ie.)

waste from the construction industry accounts for about 12–14.7 million tonnes. Per capita waste generation in major Indian cities ranges from 0.2 to 0.6 kg. In addition, the hazardous waste generation is around 4.4 million tonnes. In the future, every country must understand the importance of energy and waste management to sustainability. Moreover, in many countries, *leachate* (a liquid, mostly water, that seeps out from the base of land-filled waste or composting material) management is not given proper attention, leading to pollution of ground water. Note that some leachates can be 1000 times the strength of sewage, especially from young, rapidly filled, and/or quite dry landfills (http://www.leachate.co.uk).

According to the US Environmental Protection Agency (USEPA), construction and demolition waste, which is made up primarily of concrete, asphalt, wood, gypsum, demolition metals, and asphalt shingles, was estimated to be 325 million tons in 2003. (Construction waste is generated at the rate of about 0.5 ton/person each year in the United States.) Construction and demolition waste makes up 25%–45% of the waste that goes into US national landfills, thus contributing to the reduced life and increased environmental impacts of landfills across the United States. This waste has to be transported, thus consuming more energy and pollution. (Transportation consumes about 40% of primary US energy consumption.) While the situation is not so acute in India at present, increasing urbanization may push the country in that direction.

The Construction Materials Recycling Association, Lisle, Illinois, estimates that more than 105 million tons of concrete are recycled in North America every year. Methods of recycling concrete and concrete components are discussed in Swamy[20] and Sakai and Sordyl.[21] Recycling of concrete is a relatively simple process. It involves breaking, removing, and crushing existing concrete into materials of specified size and quality. Figure 3.11 shows the typical flow of a concrete recycling system.[22]

The quality of concrete with recycled concrete aggregates (RCAs) depends greatly on the quality of the recycled material used. RCAs have been successfully used in

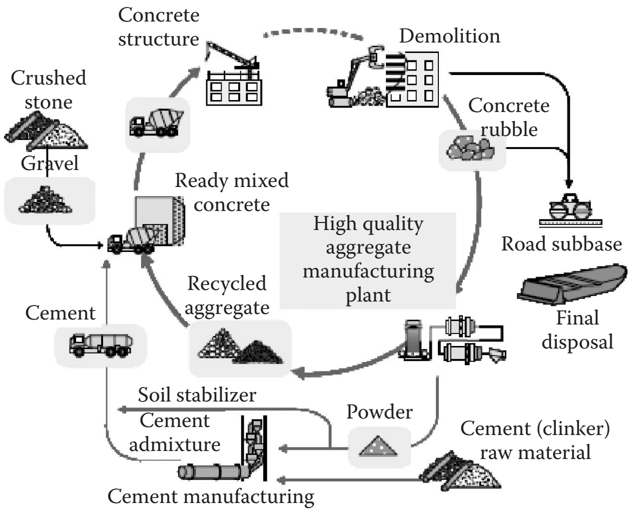


FIGURE 3.11 Schematic flow of concrete recycling system. (From Shima, H. et al., *Journal of Advanced Concrete Technology*, 3 (1): 53–67, 2005. With permission.)

applications such as bulk fills, bank protection, base or fill for drainage structures, road construction, noise barriers, and embankments. Often, recycled aggregate is combined with virgin aggregate when used in new concrete. The Texas Department of Transportation has been using RCA in concrete highways and streets and as a base material for the past 10 years and has found that it provides engineering, economic, and environmental benefits. RCAs usually present greater porosity and absorption and lower density and strength than natural aggregates. Microstructural studies on RCAs have indicated differences in the characteristics of the interfacial transition zones between the cement paste and the aggregates. It was also found that the reduction in concrete stiffness is higher than the strength, resulting in concretes with higher drying shrinkage and creep.[23] More details about recycling of concrete are provided elsewhere.[24]

Recycling concrete not only conserves resources but also saves landfill space. Use of manufactured sand, dredged sand, and mining wastes in place of river sand is also an environmentally friendly option. Several other by-products have also been successfully used with concrete. These include used foundry sand and cupola slag from metal-casting industries; postconsumer glass; wood ash from pulp mills, saw mills, and wood product manufacturing industries; sludge from primary clarifiers at paper mills; and de-inking solids from paper-recycling companies.[25] It is to be noted that recycling is not the best option because it also requires energy for processing, transportation, etc.

Many cement plants maintain a norm of zero water discharge and have transformed old abandoned mines into huge reservoirs and water bodies. ACC Ltd. in India treats its wastewater and recycles it and hence is self-reliant with respect to its water requirements.

3.3 CARBON DIOXIDE REDUCTION

Carbon dioxide is present in the atmosphere naturally due to the following:

- Anaerobic bacteria decomposing other organic matter
- Animals and people exhaling carbon dioxide during respiration
- Occasional volcanic activity

Carbon dioxide is removed naturally by plants consuming it in the process of photosynthesis and water in the oceans acting like a sink to dissolve carbon dioxide.

However, the burning of fossil fuels for producing energy required for electricity and transportation generates additional carbon dioxide as a by-product, which is not possible for Mother Nature to remove. As a result, the amount of carbon dioxide present in the atmosphere is now about 35% higher than it was a century and a half ago. The UN IPCC, in its reports issued in 2013 and 2014, warned that our planet will face devastating consequences if immediate steps are not taken to reduce the level of atmospheric carbon dioxide, which is the main cause of global warming. Under the Kyoto Protocol, industrialized countries agreed to reduce their collective GHG emissions by 5.2% compared to the year 1990.

Carbon capture and storage, also called *sequestration*, is one of the technologies being developed to reduce CO_2 emissions into the atmosphere. It involves the separation of CO_2 from other gases emitted in the coal combustion or gasification process and storing it in deep underground geological formations, in deep ocean masses, or in the form of mineral carbonates. The National Energy Technology Laboratory has estimated that North America has enough storage capacity at our current rate of production for more than 900 years' worth of carbon dioxide.

Buildings consume 40% of the world's energy and materials. Building use represents about 70% of total human consumption (energy, water, and materials combined). The carbon emissions from the production and transport of construction materials are a significant part of the construction industry. The building sector of North America was responsible for annual carbon dioxide emissions of 671 million tons of carbon in 2003, which is 37% of the total North American carbon dioxide emissions and 10% of global emissions. US buildings alone are responsible for more carbon dioxide emissions than the total carbon dioxide emissions of any other country in the world, except China.[26] In 2003, buildings were responsible for 615 million t of carbon (Mt C) emitted in the United States, 40 Mt C in Canada, and 17 Mt C in Mexico, for a total of 671 Mt C in North America. According to the International Energy Agency, total energy-related emissions in North America in this year were 1815 Mt C. Therefore, buildings were responsible for 37% of energy-related emissions in North America[26] and for 72% of US electricity consumption and 54% of natural gas consumption. When combined, materials production and transport make up 44% of all construction-related emissions (cars are responsible for only a third of all emissions). This can be reduced by improved extraction, manufacturing, and sourcing processes; recycling; and sourcing locally.

Carbon dioxide is the principal emission from the cement industry. CO_2 is released when limestone is heated to produce calcium oxide during the production of cement, as shown in the following reaction:

$$CaCO_3 + O_2 + \text{heat } (1200°C–1400°C) \rightarrow CaO + CO_2$$

About 60% of CO_2 produced in cement manufacture arises from this calcination reaction itself, and the rest is due to the high temperature needed to drive the calcination of limestone. Globally, the cement industry contributes approximately 5% to all industrial CO_2 emissions. The major environmental burdens resulting from the production of a tonne of Portland cement include[27]

- Emission of about 1 tonne of carbon dioxide (see Table 3.1)
- Use of 1700 kWh of primary energy
- Extraction of 1.5 tonne of minerals
- Requirement of about 4 GJ of energy

Worldwide, the concrete industry consumed nearly 2.77 billion tonnes of cement in 2007, and hence the carbon footprint of the industry is very high (see also Figure 3.12, which shows CO_2 emissions of some selected countries[28]). By 2006, cement production contributed to roughly 8% of worldwide anthropogenic CO_2 emissions or 6% of total anthropogenic GHG emissions. Despite significant improvements in efficiency, cement-related emissions are expected to increase.

In addition, cement production requires mining large quantities of raw materials such as limestone and clay and fuel such as coal, resulting in deforestation and topsoil loss. The concrete industry also uses large amounts of potable water for washing aggregates, mixing, and curing. Typical concrete mixes contain 12%–15% cement and 75%–80% aggregates by mass. Globally, sand, gravel, or crushed rock is used at the rate of 10–11 billion tons every year. Admixture ingredients in concrete generally comprise only a tiny percentage of concrete weight. These admixtures are mildly poisonous in their dosage stage but become harmless once bound into hydration products.

TABLE 3.1
Approximate CO_2 Emissions Associated with Production of 1 tonne of Portland Cement

Source	CO_2 Emitted (kg)	Comment
Chemical decomposition (breakdown of limestone)	500	The major source of CO_2 and intrinsically unavoidable.
Fuel	350	Use of waste as fuel can benefit sustainability.
Electricity	80	The CO_2 is normally emitted off-site at a power station.
Total	930	

Source: Higgins, D. Sustainable concrete: How can additions contribute? The Institute of Concrete Technology, U.K., Annual Technical Symposium, March 28, 2006.

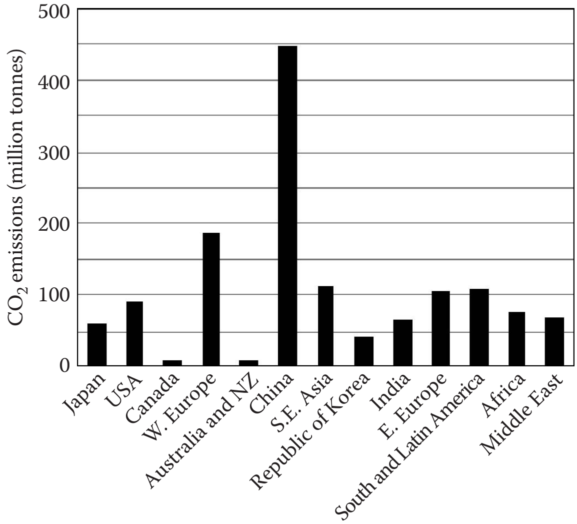


FIGURE 3.12 CO_2 emissions due to cement production in the year 2000. (From Humphreys, K. and Mahasenan, M. Toward a sustainable cement industry. Climate Change Sub-Study 8, World Business Council for Sustainable Development, 2002. With permission.)

The environmental impacts of the production of concrete may be reduced by the following (http://www.sustainableconcrete.org.uk):

- Reducing the amount of GHGs emitted during the manufacture of cement. (About 55 US plants are using *blast furnace* or *iron slag* as a raw material, and over 50 plants are using *fly ash* from electric power plants. According to the Portland Cement Association [PCA], many plants meet 20%–70% of their energy requirements with alternative fuels, such as consumer wastes—for example, tires and solid and liquid wastes [solvents]—or by-products from other industries, sewage pellets, refuse-derived fuels, etc. Cement plants also use other alternatives, such as copper slag, foundry sand, mill scale, sandblasting grit, and synthetic gypsum.)
- More efficient use of resources in concrete production, including reused materials and by-products from other industrial processes (such as *ground granulated blast-furnace slag* [*GGBS*], a by-product from the blast furnaces used to make iron and fly ash).
- Better reuse of waste and other secondary materials such as water, aggregate, fuel, or other cementitious materials.
- Lower reliance on quarrying material or sending construction and demolition waste to landfills by maximizing the use of recycled material where practical.
- Development of low-energy, long-lasting yet flexible buildings and structures.
- Exploiting the thermal mass of concrete in a structure to reduce energy demand.
- Environmental restoration after industrial activity has ceased.
- Enhancing the design service life of structure, from the current 50–60 years to about 100–120 years, by using durable materials.

The PCA reports that many US cement companies have developed closure plans for quarries that include careful soil and water contouring to optimize the environmental benefits of the reclaimed areas.[29] Dust emission during cement production has also been substantially reduced over the years. Cement kiln dust (CKD) is the material removed from the kiln exhaust gases by pollution control devices. The cement industry also has developed methods to recycle CKD back into the process, offsetting the use of limestone and other raw virgin materials and thus conserving energy. According to the PCA, from 1972 to 2006, the cement industry reduced energy consumption by 37.5%, which means that CO_2 was reduced by nearly the same amount.

Fly ash, pozzolans, granulated blast furnace slag, silica fume, and volcanic ash can also be blended with cement in cement manufacturing process by intergrinding clinker with one or more of these additives. The use of blended cements results in reduced CO_2 emissions, reduced energy consumption, and expanded production capacity (see Table 3.2); the properties of both fresh and hardened concrete are also enhanced. However, when concretes with cementitious materials are used, proper attention has to be given for curing because these concretes require more curing time to develop the required strength. Blended cements are very common in Europe and are being introduced in the United States. In India, the proportion of blended cement to total cement produced increased from 32.58% in 1999 to about 56% in 2005 and is likely to increase even more.

Moreover, during its life cycle, concrete reabsorbs about 20% of the CO_2, thus partially mitigating the effect during manufacturing. See Chapter 2 of this book/volume for more discussion on CO_2 intake of concrete.

By simultaneously using the following three tools, major reductions in concrete consumption and carbon emissions can be achieved (see Table 3.3)[30]:

- *Consuming less concrete by rehabilitating old buildings*: Increasing the service life of concrete structures from the present 50 years to 100–150 years, and enhancing the long-term durability (by careful selection of constituents of concrete), is one of the best ways to improve sustainability. Use of demountable precast products that can be reused is also an efficient solution.
- *Consuming less cement in concrete mixtures*: Using high-range water-reducing admixtures to reduce 20%–25% of water and thereby reducing

TABLE 3.2
Calculated Environmental Impacts for 1 tonne of Concrete

Impact	100% PC	50% GGBS	30% Fly Ash
GHG (CO_2)	142 kg (100%)	85.4 kg (60%)	118 kg (83%)
Primary energy use	1070 MJ (100%)	760 MJ (71%)	925 MJ (86%)
Mineral extraction	1048 kg (100%)	965 kg (92%)	1007 kg (96%)

Source: Higgins, D., Sustainable concrete: How can additions contribute? The Institute of Concrete Technology, U.K., Annual Technical Symposium, March 28, 2006.

TABLE 3.3
Projected Cement and CO_2 Reduction

Description	Year 2010	Year 2030	Percentage Reduction
Cement requirement (billion tonnes)	2.8	1.96	30
Clinker factor[a]	0.83	0.60	27
Clinker requirement (billion tonnes)	2.3	1.18	49
CO_2 emission factor[b]	0.9	0.8	10
Total CO_2 emission (billion tonnes)	2.07	0.94	55

Source: Mehta, P. K., *Concrete International*, 31 (2): 45–48, 2009. With permission from the American Concrete Institute.

[a] Tonnes of clinker per tonne of cement.

[b] Tonnes of CO_2 per tonne of clinker.

cement content, optimizing aggregate size and grading, and using 56- to 90-day compressive strength instead of the traditional 28-day strength (especially in PPC) may result in 15%–20% cement savings.

- *Minimizing the quantity of cement in a concrete mix*: The use of industrial by-products such as fly ash, blast furnace slag, silica fume, reactive rice husk ash, etc., can lead to significant reductions in the amount of cement needed to make concrete and hence reduce emissions of CO_2 and consumption of energy and raw materials, as well as reduce landfill/disposal burdens. (India produces over 270 million tonnes of fly ash per year, which is harmful and difficult to dispose of.) Fly ash can be readily substituted for over 30% of cement volume and blast furnace slag for more than 35%. High-volume fly ash concretes with 50%–70% of cementitious content have been studied extensively, and their use has been found to be feasible in certain situations; they have been found to have better properties than concretes produced with Portland cement.[31]

Table 3.3 is based on the following assumptions: Combined use of tools 1 and 2 will reduce cement consumption by 30% (2.80 billion tonnes in 2010 to 1.96 billion tonnes in 2030). Clinker factor is reduced by 20%–30% by the use of alternate cementitious materials. The carbon emission factor is decreased by 10%–20% by the use of waste material as fuel.

3.3.1 "Green" Cements[28]

As discussed already, sequestration is a process that involves capturing the CO_2 from coal-fired power plants, compressing it into a liquid, and injecting it deep beneath the earth into old oil fields or saline aquifers. Cement companies around the world are in the process of commercializing cements that either absorb more than their production generates or do not emit carbon dioxide at all. A company called Calix, based in Sydney, Australia, has recently filed a patent to produce "green" cement through the rapid calcination of calcium magnesium carbonate particles known as dolomite.

According to the company, the particles are dropped into a vertical tube full of superheated steam, which causes the particles to explode into grains, increasing the overall surface area. These grains then react with the steam, oxidizing the surfaces. The residue is then ground into a powder and mixed with sand to form a powder known as Semidolime. To produce the cement, Semidolime is mixed with water and power-plant flue gas, which typically contains significant levels of CO_2.

The company claims that the fuel and electricity used during the process generate 14 kg of CO_2 for every tonne of concrete ultimately produced; this cement absorbs 21 kg of CO_2 per tonne of material as it hardens into concrete of the desired shape. The net result is that for every tonne of concrete produced, the material removes 7 kg of CO_2 from the atmosphere.

Another company, called Calera and based in Los Gatos, California, has developed a technique to absorb the CO_2 in hot power plant flue gas with hard water to make cement. The CO_2 reacts with calcium and magnesium in the water to form solid carbonates and bicarbonates, which are then removed from the water and processed for use as cement, without any CO_2 having been produced in the process.

A London-based company, Novacem, has built a small pilot plant at Imperial College and replaced the limestone used in conventional Portland cement with magnesium silicates. (Half of that CO_2 is released in the calcination of limestone; the other half comes from the fuel used to heat the reaction.) Magnesium silicates, in contrast, release far less CO_2 when heated. To produce cement, the magnesium silicates are heated to 180°C, causing them to form magnesium carbonates. These are then further heated to 700°C to produce magnesium oxide, producing a small amount of CO_2 in the process. The resulting cement is a mixture of this magnesium oxide and some magnesium silicates.

Researchers from IIT-Delhi, IIT-Bombay, and IIT-Madras collaborating with the Swiss Federal Institute of Technology in Lausanne and the Central University of Las Villas in Cuba are developing a new blend of cement that will reduce the carbon footprint of cement by 40%. The new blend, a combination of calcined clay and ground limestone (which the researchers call LC3 for limestone calcined clay clinker cement), is expected to replace half of the Portland cement. Use of LC3 will lower carbon dioxide emission, lower cost because the substitution material is abundantly available, and lower capital because no change of equipment or additional training of construction workers is required. The researchers also expect it to be energy efficient as lesser energy will be required to manufacture and manage industrial waste, as there is a possibility of using existing mining and other wastes. It will also extend the life of limestone reserves.

The use of ready mixed concrete can also help in obtaining quality concrete that will increase the durability and life of concrete structures. Modern concretes such as fibrous concrete, geopolymer concrete, high-performance concrete, reactive powder concrete, self-compacting concrete, self-curing concrete, etc., not only enhance the properties of concrete but also increase the life of structures built with them.

3.3.2 Geopolymer Concrete

Clinker is made by calcining calcium carbonate (limestone), which releases CO_2 into the atmosphere. Mineral polymers can be made from inorganic alumino-silicate (Al-Si) compounds. An inorganic polycondensation reaction results in a three-dimensional structure, like that of zeolites. It can be produced by blending three elements: calcined aluminosilicates (from clay), alkali-disilicates, and granulated blast furnace slag or fly ash.[32] The cement hardens at room temperature and provides compressive strengths of 20 MPa after 4 h and up to 70–100 MPa after 28 days.[32] The geopolymer technology was proposed as a greener alternative binder to Portland cement with applications in the concrete industry.[33]

Geopolymer binder can be used in applications to replace or partially replace ordinary Portland cement with environmental and technical benefits, including an 80%–90% reduction in CO_2 emissions. This is mainly due to the absence of the high-temperature calcination step in geopolymer synthesis. The silicon and aluminum oxides in the low-calcium fly ash chemically react with the alkaline liquid to form the geopolymer paste that binds the loose coarse aggregates, fine aggregates, and other unreacted materials together to form the geopolymer concrete.[34] Heat-cured, low-calcium, and fly ash-based geopolymer concrete has excellent compressive strength; suffers very little drying shrinkage and low creep; and has excellent resistance to sulfate attack and good acid and fire resistance.[35] Despite the high alkali content, mineral polymers do not show alkali aggregate reactions. During 2008, a company called Zeobond launched the commercial production of geopolymer concrete in Melbourne, Australia under the brand name E-Crete™. It is interesting to note that structures using similar geopolymer concretes were constructed in ancient Rome, as well as in the former Soviet Union in the 1950s and 1960s, and are still in service.

3.3.3 Photocatalytic Concrete

"Depollution" is the opposite of pollution and means the removal of contaminants and impurities from the environment. The newest tool for achieving depollution is a photocatalyst, a material that uses solar energy to accelerate chemical reactions without being consumed or depleted in the process. Photocatalytic concrete, made using the patented Portland cement developed by Italcementi Group, has been introduced in the United States under the name TX Active.[36]

Photocatalytic concrete has, in addition to Portland cement binders, a proprietary formulation of photocatalytic titanium dioxide particles. When used on or in a concrete structure, these photocatalyst particles oxidize volatile organic compounds and nitrogen oxides (NO_x), thus eliminating unhealthy ozone at the source. It also oxidizes inorganic compounds such as SO_x, CO, NH_3, and H_2S, as well as chlorinated organic compounds. These catalyzed compounds break down into oxygen, carbon dioxide, water, sulfate, nitrate, and other molecules that are beneficial to or, at worst, have a relatively gentle impact on the environment.[37]

Photocatalytic concrete has other environmental benefits, such as reflecting much of the sun's heat and reducing the heat gain associated with dark construction materials. This keeps cities cooler, reduces the need for air conditioning, and reduces smog.

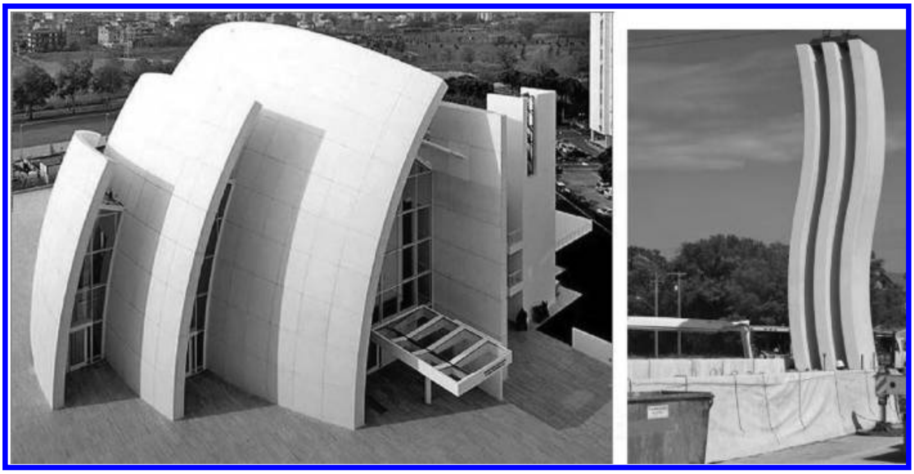


FIGURE 3.13 Jubilee Church in Rome and the gateway sculptures at the new I-35W bridge at Minneapolis, where self-cleaning photocatalytic concrete has been used. (From http://www.concretedecor.net; http://projects.dot.state.mn.us/35wbridge.)

White precast concrete is also attractive as an interior finish because it can improve the efficiency of lighting, reduce energy requirements, neutralize indoor air pollutants, and help sustainable design initiatives.[36]

Figure 3.13 shows Jubilee Church in Rome and the gateway sculptures at the new I-35W bridge at Minneapolis, Minnesota, built using photocatalytic concrete.

3.4 SUSTAINABLE DEVELOPMENT

A number of solutions have been suggested and some successfully implemented in the past in several countries to produce clean energy and to maintain sustainability. These solutions include building more nuclear power plants, geothermal power and heat, solar heating and cooling, wind power, modern forms of bioenergy, solar photovoltaics, advanced biomass gasification, biorefinery technologies, solar thermal power stations, hot-dry-rock geothermal power, and ocean energy. Development of alternative fuels such as biodiesel, bioalcohol (ethanol, butanol), chemically stored electricity (batteries and fuel cells), hydrogen, nonfossil methane, nonfossil natural gas, vegetable oil, and other biomass sources has also been attempted. Each one has its advantages and drawbacks. In the following, we shall discuss only a few of these suggestions and will confine the discussion to sustainable construction and the role of concrete.

The building and construction sector generates substantial social and economic benefits, employing over 111 million people worldwide and contributing approximately 10% to the global gross domestic product (GDP).[13] At the same time, the built environment contributes significantly to global raw materials use, energy use, solid waste generation, and GHG emissions (Figure 3.14).[13]

More than any other human endeavor, the built environment has direct, complex, and long-lasting impacts on the biosphere. Some 10% of the global economy is devoted to construction, and about one-half of world's major resources are consumed

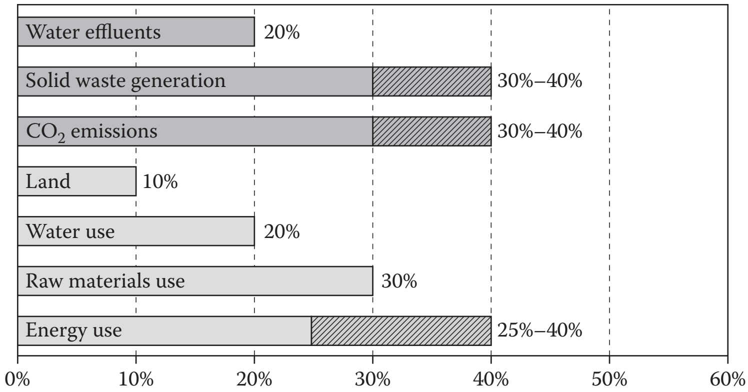


FIGURE 3.14 Share of the built environment in pollution emission and resource use. (From World Resources Institute. Available at http://earthtrends.wri.org/updates/node/264 [accessed Feb. 12, 2009].)

by construction and related industries. It is estimated that, in the United States, the building industry involves the extraction and movement of 6 billion tons of basic materials annually (representing 8% of US GDP and 40% of extracted material[2]); residential and commercial buildings together use one-third of all energy and two-thirds of all electricity consumed in the country. They also account for 47% of sulfur dioxide emissions, 22% of nitrogen oxide emissions, and 10% of particulate emissions, all of which damage air quality.[8] Further, as mentioned earlier, buildings produce 35% of the country's carbon dioxide emissions—the chief pollutant blamed for climate change. IAQ is inadequate in 30% of the buildings around the world. These statistics underline the importance of changing construction practices.

To address these challenges, there is a need to develop effective approaches for life cycle design and management of construction that will ensure their sustainability in terms of improved physical performance, cost effectiveness, and environmental compatibility. LCA and design are discussed in Chapter 11. More details about LCA may be found in Curran.[38] Sustainable design has to consider three major aspects of sustainability: social, economic, and environmental (see Figure 3.15).

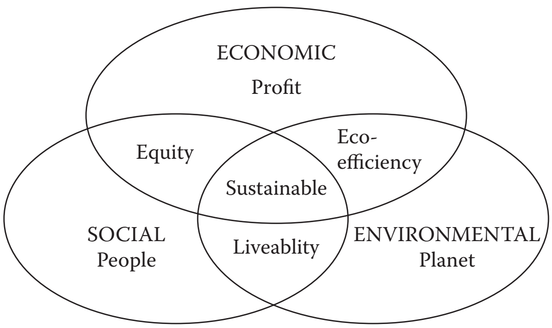


FIGURE 3.15 Three pillars of sustainability: economic, social, and environmental.

The following are considerations for a sustainable building (SB) design[2]:

- Resources should be used only at the speed at which they naturally regenerate and discarded only at the speed at which local ecosystems can absorb them.
- Site planning should incorporate resources naturally available on the site, such as solar and wind energy, natural shading, and drainage.
- Resource-efficient materials should be used in the construction of buildings and in furnishings to lessen local and global impact.
- Energy and material waste should be minimized throughout a building's life cycle, from design through reuse or demolition.
- The building shell should be designed for energy efficiency, considering factors such as day lighting, passive ventilation, building envelope, internal load, local climate, etc.
- Material and design strategies should produce excellent indoor environmental quality (IEQ).
- The design should maximize occupant health and productivity.
- Operation and maintenance systems should support waste reduction and recycling.
- Water should be managed as a limited resource.
- Location and systems should optimize employee commuting and customer transportation options and minimize the use of single-occupancy vehicles. These include using alternative work modes such as telecommuting and teleconferencing.

The preceding design considerations show that there should be effective interaction among all the persons involved in the project (client, architect, structural engineer, electrical and mechanical engineers, landscape architect, and others) at all stages of the project. For concrete structures to be really sustainable, one should adopt the holistic approach to the design based on the principle of *strength through durability* rather than *durability through strength*.[20]

3.5 GREEN BUILDING RATING SYSTEMS

To promote design and construction practices that reduce the negative environmental impacts of buildings and improve occupant health and well-being, the USGBC, a nonprofit coalition of building industry leaders based in Washington, District of Columbia, developed the LEED® green building rating system in 1993. In the United States and in a number of other countries around the world, LEED certification is the recognized standard for measuring building sustainability. Similar assessment systems are available in other countries (e.g., the British green building rating system developed by Building Research Establishment [BRE] in 1992 called the BRE Environmental Assessment Method [BREEAM], the Comprehensive Assessment System for Building Environmental Efficiency [CASBEE] of Japan, and Green Star of Australia). All these systems are designed to encourage construction of green buildings that will minimize disruption of local ecosystems; ensure the efficient use of water, energy, and other natural resources; and ensure healthy indoor environment.

However, they differ in terminology, structure, assessment of performance, points assigned to different performance criteria, and documentation required for certification. These systems, while voluntary in nature, continue to gain recognition. It is interesting to note that adoption of these systems also results in economic incentives as owners and renters increasingly demand facilities with high green building ratings.

3.5.1 LEED-NC

From 1994 to 2006, LEED grew from one standard for new construction to a comprehensive system of six interrelated standards covering all aspects of the development and construction process: LEED-NC for new construction, LEED-EB for existing buildings, LEED-CI for commercial interiors, LEED-H for homes, LEED-CS for core and shell projects, and LEED-ND for neighborhood development.[2] LEED-NC, which was originally developed for office buildings, but is used for all types of buildings except single-family homes, is briefly discussed next.

LEED-NC 2.2, issued in 2005, is structured with seven prerequisites and a maximum of 69 points divided into the following six major categories: energy and atmosphere (17 maximum points), IEQ (15 points), sustainable sites (14 points), materials and resources (13 points), water efficiency (5 points), and innovation and design process (5 points). A building is LEED certified if it obtains at least 26 points. Silver, gold, and platinum levels are awarded for at least 33, 39, and 52 points, respectively, as shown in Table 3.4. It must be noted that LEED is continuously evolving and improving. The most recent update to the rating systems (LEED v4) was launched in November 2013 and opened LEED to a wider range of building types and manufacturing industries, delivering the benefits of green building up and down the supply chain. It advances environmental footprint issues, like climate change, and encourages optimization of energy and water use. (Note that pervious concrete and water conservation are discussed in Chapter 7, and concrete and heat island effects are discussed in Chapter 8.)

The task of selecting building materials and products for a high-performance green building is the most difficult and challenging for any design team. Several tools are available for this process, and one of the best tools is the life cycle assessment (LCA). LCA provides information about the resources, emissions, and other impacts resulting from the life cycle of material use, from extraction to disposal. Hence, one must consider the impact of the material from extraction to disposal. One such LCA program is the building for environmental and economic sustainability software.[39] Ideally, the material cycle should be closed looped and waste free. Thus, the following rules apply while selecting the materials for green construction:

- They should consume the least energy to manufacture.
- They should not involve long-distance transportation (for the raw materials as well as finished product).
- The natural resources and the raw materials used should not affect the environment.
- They must be easy to recycle and safe to dispose in landfills.
- They should be harmless in production and use.

TABLE 3.4
Overview of LEED-NC 2.2 Categories and Credits

Sustainable Sites: 14 Points	
Construction activity: Pollution prevention	Required
Credit 1: Site selection	1
Credit 2: Development density and community connectivity	1
Credit 3: Brownfield redevelopment	1
Credit 4.1: Alternative transportation, public transportation	1
Credit 4.2: Alternative transportation, bicycle storage, and changing rooms	1
Credit 4.3: Alternative transportation, low-emitting and fuel-efficient vehicles	1
Credit 4.4: Alternative transportation, parking capacity	1
Credit 5.1: Site development, protect or restore habitat	1
Credit 5.2: Site development, maximize open space	1
Credit 6.1: Storm-water design, quantity control	1
Credit 6.2: Storm-water design, quality control	1
Credit 7.1: Heat island effect, nonroof	1
Credit 7.2: Heat island effect, roof	1
Credit 8: Light pollution reduction	1
Water Efficiency: 5 Points	
Credit 1.1: Water-efficient landscaping, reduce by 50%	1
Credit 1.2: Water-efficient landscaping, no potable use or no irrigation	1
Credit 2: Innovative wastewater technologies	1
Credit 3.1: Water use reduction, 20% reduction	1
Credit 3.2: Water use reduction, 30% reduction	1
Energy and Atmosphere: 17 Points	
Prerequisite 1: Fundamental commissioning of the building energy systems	Required
Prerequisite 2: Minimum energy performance	Required
Prerequisite 3: Fundamental refrigerant management	Required
Credit 1: Optimize energy performance	1–10
Credit 2: On-site renewable energy	1–3
Credit 3: Enhanced commissioning	1
Credit 4: Enhanced refrigerant management	1
Credit 5: Measurement and verification	1
Credit 6: Green power	1
Materials and Resources: 13 Points	
Prerequisite 1: Storage and collection of recyclables	Required
Credit 1.1: Building reuse, maintain 75% of existing walls, floors, and roof	1
Credit 1.2: Building reuse, maintain 95% of existing walls, floors, and roof	1
Credit 1.3: Building reuse, maintain 50% of interior nonstructural elements	1
Credit 2.1: Construction waste management, divert 50% from disposal	1
Credit 2.2: Construction waste management, divert 75% from disposal	1
Credit 3.1: Materials reuse, 5%	1
Credit 3.2: Materials reuse, 10%	1

(*Continued*)

TABLE 3.4 (CONTINUED)
Overview of LEED-NC 2.2 Categories and Credits

Credit 4.1: Recycled content, 10% (postconsumer + 1/2 preconsumer)	1
Credit 4.2: Recycled content, 20% (postconsumer + 1/2 preconsumer)	1
Credit 5.1: Regional materials, 10% extracted, processed, and manufactured	1
Credit 5.2: Regional materials, 20% extracted, processed, and manufactured	1
Credit 6: Rapidly renewable materials	1
Credit 7: Certified wood	1
IEQ: 15 Points	
Prerequisite 1: Minimum IAQ performance	Required
Prerequisite 2: Environmental tobacco smoke control	Required
Credit 1: Outdoor air delivery monitoring	1
Credit 2: Increased ventilation	1
Credit 3.1: Construction IAQ management plan, during construction	1
Credit 3.2: Construction IAQ management plan, before occupancy	1
Credit 4.1: Low-emitting materials, adhesives and sealants	1
Credit 4.2: Low-emitting materials, paints and coatings	1
Credit 4.3: Low-emitting materials, carpet systems	1
Credit 4.4: Low-emitting materials, composite wood and agrifiber products	1
Credit 5: Indoor chemical and pollutant source control	1
Credit 6.1: Controllability of systems, lighting	1
Credit 6.2: Controllability of systems, thermal comfort	1
Credit 7.1: Thermal comfort, design	1
Credit 7.2: Thermal comfort, verification	1
Credit 8.1: Daylight and views, daylight 75% of spaces	1
Credit 8.2: Daylight and views, views for 90% of spaces	1
Innovation and Design Process: 5 Points	
Credit 1.1: Innovation in design (give specific title)	1
Credit 1.2: Innovation in design (give specific title)	1
Credit 1.3: Innovation in design (give specific title)	1
Credit 1.4: Innovation in design (give specific title)	1
Credit 2: LEED-accredited professional	1
Project total: 69 total points possible	
Certified: 26–32 points; silver: 33–38 points; gold: 39–51 points; platinum: 52–69 points	

Source: Available at http://www.usgbc.org.
Note for EAc1: All projects registered after June 26, 2007 are required to achieve at least 2 points.

- Materials dissipated from recycling must be harmless.
- They should have long life and durability.
- Buildings must be able to be deconstructed.
- Building components must be easy to disassemble.

It may be difficult to identify a material that fulfills all of the preceding requirements. In particular, the last rule of disassembly has not been considered in

TABLE 3.5
Summary of Possible Points to Increase LEED Ratings of Buildings

Category	Total Points	Points Earned Using Concrete
Sustainable sites	14	2
Water efficiency	5	0
Energy and atmosphere	17	10
Materials and resources	13	6
IEQ	15	0
Innovation credits	4	0
LEED-accredited professional	1	0
Total	69	18

Source: Vangeem, M. G., and M. L. Marceau, *Concrete International* 24 (11): 69–73, 2002. With permission from American Concrete Institute.

traditional building materials, except prefabricated steel structures. Disassembly also discourages the use of composite materials. Recently, a construction method for demountable concrete buildings was developed in Germany with the use of aluminum foam.[40–42] It has been shown that, by using concrete, one can earn up to 18 points (out of the 26 required) toward an LEED-certified building (see Table 3.5).[43]

Green buildings adopt various strategies for water management: using low-flow or ultralow-flow plumbing fixtures and electronic controls and fixtures, substitution of alternative water sources (rainwater, reclaimed water, and gray water) for potable water, rainwater harvesting, xeriscaping, and use of other technologies and approaches that result in reduction of potable water consumption.[2]

3.5.2 LEED-ND

The existing LEED system is geared toward specific buildings, which earn points toward certification by using such green features as recycled building materials, pervious pavements, low-flush toilets, and green roofs. The USGBC recently approved new guidelines for LEED for neighborhood development (LEED-ND); introduced in April 2009, they give more weight to factors that affect energy efficiency and GHG emissions. Extra points are also given to buildings that deal with local environmental conditions such as low water use features in dry regions. LEED-ND adopts a new system where the credits are weighted according to LCA indicators. The LEED-ND rating system has 109 points, including 9 prerequisites, compared with 69 points for LEED-NC. LEED-ND is divided into four point categories: smart location and linkage, neighborhood pattern and design, green construction and technology, and innovation and design process. The number of points that a building will now get will be different for every building depending on its materials, their durability, etc.

Projects must be in a "smart" location near water and wastewater facilities. Developing on farmland or a floodplain is forbidden, compact development is a must, wetlands have to be preserved, and "imperiled" species must not be disturbed. Points toward certification can be gained for things such as wetland restoration (1 point), brownfield redevelopment (2 points), housing and job proximity (3 points), diversity of uses (4 points), and reduced car dependence (8 points). LEED-ND certification levels include certified (40–49 points), silver (50–59 points), gold (60–79 points), and platinum (80–106 points).

3.5.3 Green Building Initiative Green Globes™

Green Globes is an outgrowth of the BREEAM, which was developed in the United Kingdom. It is a web-based assessment and rating tool for green building performance. It was developed in Canada and is being introduced to the US market as an alternative to the USGBC's LEED rating system. This online tool was first developed by the Green Building Initiative (GBI), Canada, during 2000. It was revised and released in 2002 by a team of experts including representatives from Arizona State University, the Athena Institute, Building Owners and Managers Association (BOMA) of Canada, and several federal departments (http://www.greenglobes.com).

Green Globes consists of a series of seven questionnaires on topics such as project management, site, energy, water, resources, emissions, and indoor environment. The questionnaire corresponds to a checklist with a total of 1000 points listed in the seven categories given previously (see Figure 3.16). Once each questionnaire is completed, the online system automatically generates a report, which contains a recommendation for improvement and additional supplementary information. The report also contains the overall score of the project as well as percentage scores in each category, as shown in Figure 3.16. Thus, it serves as a virtual consultant and provides instant feedback. The straightforward questionnaire format is easy to complete even if one does not have an environmental design background or experience. Note that the largest number of points is allocated to energy, followed by indoor environment.

Unlike LEED, however, the actual number of points available varies for different projects. Thus, Green Globes does not penalize projects for strategies that are

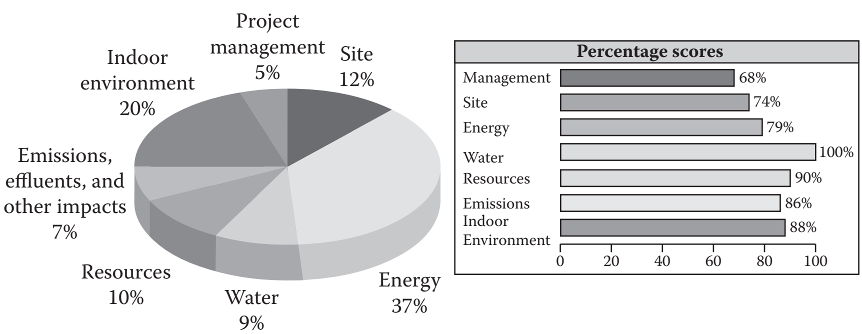


FIGURE 3.16 Distribution of points and percentage scores generated by Green Globes web tool. (From http://www.greenglobes.com. With permission.)

not applicable. For example, points are available for exterior lighting to avoid glare and sky glow; however, if a project has no exterior lighting, the user can select the option "N/A," which removes those points from the total number of available points.

Based on the percentage of points achieved, projects are assigned a rating of one or more green globes. In Canada, the ratings range from one to five green globes. However, in the United States, the lowest rating has been eliminated and the rest adjusted so that the highest rating is four globes. Independent third-party verification by a trained and licensed engineer or architect with significant training and experience is required before receiving the final rating. After reviewing the existing supporting documents (such as working drawings, building specifications, waste disposal plans, evidence of energy, and life cycle modeling), the verifier may confirm the percentage of points obtained through the online assessment report.

It has to be noted that Green Globes is broader in its technical content than LEED since it allocates points for issues such as optimized use of space, acoustical comfort, and an integrated design process. Green Globes is unique in providing LCA tools that quantify the cradle-to-grave implication of building materials selection in terms of CO_2 emission potential, embodied primary energy, pollution of air and water, and weighted resource use on the environment.[21] It is difficult to compare the points achieved in LEED and Green Globes because they are organized differently. Moreover, the precise requirements of Green Globes are not transparent.

Several buildings have obtained Green Globes certification. The Integrated Learning Center at Queen's University in Kingston, Ontario, designed by B+H Architects of Toronto, received a four-globe rating in 2004. More details about the energy-efficient systems, water conservation features, resources used, and source control of indoor pollutants of this building, as well as other Green Globe-certified buildings, may be found at http://www.thegbi.org.

3.5.4 Energy Star®

Energy Star is a joint program of the USEPA and the US DOE that aims to assist industry to improve competitiveness through increased energy efficiency and reduced environmental impact. Energy Star provides guidance, energy management tools, and strategies for successful corporate energy management programs. With the help of Energy Star, Americans saved $16 billion on their utility bills in 2007 alone, thus avoiding GHG emissions equivalent to those from 27 million cars (http://www.energystar.gov).

Energy Star was introduced in 1992 as a voluntary labeling program designed to identify and promote energy-efficient products to reduce GHG emissions. This label (see Figure 3.17) may be found now on equipment and appliances including computers, refrigerators and freezers, washing machines, dish washers, air conditioners, heating and cooling equipment, water heaters, home electronics, office equipment, lighting, etc. Such Energy Star-qualified products help save money and protect our environment by using energy more efficiently. The USEPA has recently extended the label to cover new homes and commercial and industrial buildings.

FIGURE 3.17 Energy Star label.

To earn the Energy Star label, a home must meet strict guidelines for energy efficiency set by the USEPA. These homes are at least 15% more energy efficient than homes built to the 2004 International Residential Code and include additional energy-saving features that typically make them 20%–30% more efficient than standard homes. Any home with three stories or fewer can earn the Energy Star label if it has been verified to meet USEPA guidelines. Energy Star-qualified homes must include a variety of energy-efficient features (such as effective insulation, high-performance windows, tightly sealed building envelope and ducts, efficient heating and cooling equipment, and efficient products) that contribute to improved home quality and homeowner comfort, as well as to lower energy demand and reduced air pollution. Independent home energy raters are available to help users choose the most appropriate energy-saving features for their homes. Additionally, these third-party raters may be engaged to conduct onsite testing and inspections to verify the energy-efficiency measures, as well as insulation, air tightness, and duct-sealing details.

Considering the cement industry, the cost of energy as part of the total production cost is significant, warranting efforts for energy efficiency. Hence, an Energy Star guide for improving the energy efficiency of cement plants has been developed.[44] PCA member companies partnered with the USEPA and developed a cement plant energy performance indicator (EPI) to improve the industry's energy efficiency. The tool helps cement plant operators identify opportunities to improve energy efficiency, reduce GHG emissions, conserve conventional energy supplies, and reduce production costs. This rating tool also allows plants to assess how efficiently the plant uses energy relative to similar plants nationwide. The rating system provides a scale of 1–100; a rating of 50 indicates average energy performance, whereas a rating of 75 or more indicates good performance. Plants receiving an EPI score of 75 or higher are eligible to earn an Energy Star recognition. This tool is available on the USEPA website (http://www.energystar.gov).

3.5.5 GBTool

GBTool, now known as the SB tool, is another performance assessment system developed by the International Initiative for a Sustainable Built Environment, an international nonprofit organization operating from Ottawa, Canada. This system, launched in 1996, is a framework operating on Excel that can be configured to suit almost any local condition or building type.

In GBTool, scores are assigned in the range of –2 to +5. The scores of –2 and –1 denote levels of performance below the acceptable level for the specified occupancy; the score of 0 is the minimum level of acceptable performance for the specified occupancy. A score of 3 indicates the best practice, and 5 is the best technically achievable, without consideration of cost (http://greenbuilding.ca/).

In order to evaluate the technical and social aspects of the resource flow of concrete, a resource flow simulation system called ecoMA has been developed in Japan. The system uses the concept of a multiagent system and is designed to focus on the decision-making dynamics between each company and government within the city scale so that social constraint of resource flow can be simulated properly. The system also uses the concept of graph theory to model the supply chain and time.[45]

It has to be noted that the existing green rating systems have been developed with little input from the concrete industry. Many of these rating systems confuse the use of concrete to achieve sustainability with the actual production of cement and techniques to reduce concrete's environmental footprint.[21] The beneficial effects, such as the thermal comfort provided by concrete due to its high thermal mass and CO_2 uptake during the operational phase of buildings, should be given proper consideration. (Thermal mass is discussed in Chapter 4.) LEED was developed with input from the wood and steel industries but not from the concrete industry.[21] Moreover, in rating systems such as LEED, the main focus is on buildings only; infrastructure applications such as bridges, dams, pavements, and roads are not yet considered.

3.6 BUILDING CODES AND GREEN DEVELOPMENT*

In their simplest form, the purpose of building codes is to ensure safe buildings. Building codes aim to provide minimum standards to safeguard life, health, property, and public welfare by regulating and controlling the design; construction; quality of materials; use and occupancy; location; and maintenance of all buildings, structures, and certain equipment within this jurisdiction. If successful, a building code can also preserve the built environment, reduce the need for government disaster aid, and maintain employment and businesses after a natural disaster. However, building codes have not historically addressed the environmental impact of buildings. Most building codes do not directly address issues such as climate change, water conservation, energy consumption, durability, storm-water impacts, and IEQ.

It is believed that the idea of a building code in the United States originated with George Washington and Thomas Jefferson, who encouraged the use of minimum standards of construction. It was not until 1905, however, when the first code as we know it today was developed by the Fire Underwriters Association.

In 1915, three organizations of code enforcement officials were created: Building Officials and Code Administrators International, International Conference of Building Officials, and the Standard Building Code Congress International. Each organization

* Erin Ashley and Lionel Lemay, both from the National Ready Mixed Concrete Association, contributed this section. Their assistance is gratefully acknowledged.

had its own model code. It was not until the International Code Council (ICC) was formed in 1994 as a nonprofit organization that a single set of comprehensive and coordinated national model construction codes was published.

As mentioned previously, building codes have not historically addressed the environmental impact of buildings. Their focus has been on the soundness and safety of the built environment rather than on the impact that the buildings will have on the natural environment. One area where the model building codes have made some progress is the energy efficiency of buildings. Energy efficiency remains one of the most important aspects of sustainable development. Any minimum standard to improve energy efficiency of buildings could significantly reduce the environmental impact of our built environment.

3.6.1 Energy Codes

The energy crisis of the 1970s resulted in the creation of the first energy code in the United States. The 1992 Energy Policy Act charged the DOE to determine whether or not the 1992 Council of American Building Officials (CABO) Model Energy Code (MEC) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1-1989, Energy Standard for Buildings except Low-Rise Residential Buildings, would improve energy efficiency for residential and commercial buildings, respectively. DOE did determine that these energy codes would improve energy efficiency in buildings.

The CABO MEC was last promulgated in 1995 and has since been replaced by the International Energy Conservation Code published by the ICC; the most recent version was published in 2009. ASHRAE Standard 90.1 was most recently published in 2007. ASHRAE also publishes ASHRAE Standard 90.2, Energy-Efficient Design of Low-Rise Residential Buildings, which was most recently published in 2007. ASHRAE Standard 189.1, Standard for the Design of High-Performance Green Buildings except Low-Rise Residential Buildings, addresses site sustainability; water use efficiency; energy efficiency; IEQ; and the building's impact on the atmosphere, materials, and resources.

States now must certify that their building codes meet the requirements in ASHRAE's 2004 energy efficiency standard, under a ruling issued by the United States DOE finding that the standard saves more energy than an earlier version. The following should be noted:

- Energy codes are becoming more stringent (saving more energy).
- Energy codes are moving to reduce GHGs.
- Energy codes will eventually require net-zero energy and carbon-neutral buildings.

3.6.2 Energy Codes and Concrete

Energy codes generally dictate minimum requirements for a building's envelope, mechanics, and lighting. They do not encourage other energy-saving strategies such as building orientation, limiting infiltration, planting trees for shading, and using passive solar design strategies. Minimum insulation levels for walls, roofs, and floors, as well as window requirements, are typically specified in the model codes and vary with climate region since more insulation is cost effective in cold or extremely hot regions.

The energy codes generally specify minimum requirements for thermal resistance (*R*-values) for walls and roofs. For walls with thermal mass (such as concrete), *R*-values are not a true indicator of energy performance. These materials have a relatively low *R*-value, yet buildings constructed with concrete walls, floors, and roofs perform well in most climates. In most climates, buildings with insulated mass walls will save energy compared to buildings without mass with the same *R*-value. In many southern and western climates, mass walls without insulation will perform as well as nonmass walls with insulation.[46]

3.6.3 Other Sustainability Standards

3.6.3.1 American Society for Testing and Materials

The American Society for Testing and Materials (ASTM) has produced numerous standards related to sustainability. These standards include testing methods and specifications for products that are potentially used in green building applications. For example, ASTM lists standards for fly ash, ground slag, and other industrial by-products as sustainability standards, even though these standards were developed long ago before green building or sustainability was a popular concept.

The ASTM Committee E60 on Sustainability, formally E06 on Performance of Buildings, has addressed sustainability in the building industry. In 2005, ASTM E2432-05, *Standard Guide for General Principles of Sustainability Relative to Buildings*, was published. The standard explains that, ideally, human activities would not require making trade-offs among environmental, economic, and social goals. However, the guide recognizes that in applying sustainability principles to buildings, decision makers must often balance opportunities and challenges associated with each of the general principles. The standard also identifies general methodologies associated with the decision-making process used in pursuing sustainability.[47]

In 2005, GBI became the first green building organization to be accredited by the American National Standards Institute (ANSI). In 2006, GBI began developing GBI Proposed American National Standards (ANS) 01-200XP: Green Building Assessment Protocol for Commercial Buildings. The ANSI process is consensus-based and involves a balanced committee consisting of 30 users, producers, and interested parties. The proposed code will also reference two new software tools that were developed to support the goals of the proposed standard: Green Globes LCA Credit Calculator and Green Globes Water Consumption Calculator. The code was formally approved on March 24, 2010.

3.6.3.2 American Concrete Institute

The American Concrete Institute (ACI), the main code-writing body for concrete in the United States, has recently recognized the need for addressing sustainability in the standards it produces and to educate its members on the subject. In its latest strategic plan, ACI identified sustainability as one of its five main goals.

In 2000, ACI formed the Board Advisory Committee on Sustainable Development with the mission to develop and recommend policies and develop information on sustainable concrete development for the Institute. One outcome of this committee was the formation of the ACI Sustainability of Concrete Committee, ACI 130, in 2008.[48] Its mission is to develop and report information on the sustainability of concrete with the goals of

- Completing a document on concrete sustainability
- Assisting other technical committees in adding sustainability content to technical documents
- Beginning holding regular workshops and sessions on sustainability in coordination with other committees
- Beginning development of an ecocalculator specific to concrete

3.6.3.3 International Organization for Standardization

The International Organization for Standardization (ISO) has published a series of standards for the environmental management of goods and services.[49] Only recently it published ISO 15392:2008, ISO 15686-6:2004, ISO/TS 21929-1:2006, ISO 21930:2007, and ISO/TS 21931-1:2006, which provide frameworks with reference to structures.[50–54]

- ISO 15392:2008 is applicable to buildings and other construction works individually and collectively, as well as to the materials, products, services, and processes related to the life cycle of buildings and other construction works.
- ISO 15686-6:2004 describes how to assess, at the design stage, the potential environmental impacts of alternative designs of a constructed asset. It identifies the interface between environmental LCA and service life planning.
- ISO/TS 21929-1:2006 provides a framework, makes recommendations, and gives guidelines for the development and selection of appropriate sustainability indicators for buildings.
- ISO 21930:2007, *Sustainability in Building Construction—Environmental Declaration of Building Products* describes the principles and framework for environmental declarations of building products, taking into consideration the complete life cycle of a building. ISO 21930 is expected to form the basis for type III environmental declaration programs of building products as described in ISO 14025:2006, *Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures.*

The overall goal of environmental declarations in this sector is to encourage the demand for and supply of building products that cause less stress on the environment, through communication of verifiable and accurate information on environmental aspects of those building products that is not misleading, thereby stimulating the potential for market-driven continual environmental improvement.

- ISO/TS 21931:2006 provides a general framework for improving the quality and comparability of methods for assessing the environmental performance of buildings.

- ISO 14000 is a group of standards that addresses environmental management and pollution prevention.
- ISO 14001 is a standard for environmental management systems to be implemented in any business, including concrete producers, concrete product manufacturers, and cement manufacturers—or any building product manufacturer, for that matter. And although the standard is not exactly related to green building, adoption of these standards by building product manufacturers and contractors could reduce the overall environmental impact of the built environment.

3.6.4 Green Building Rating Systems

As mentioned already, rating systems such as LEED, Green Globes, NAHB Green Building Standard, and Energy Star have been designed as voluntary standards and have not been written in the mandatory language typically associated with building codes and standards. However, many local jurisdictions have adopted these rating systems requiring buildings to meet a certain rating. As a result, these rating systems have in effect become codes.

It will be interesting to see over time how the courts handle these particular cases. For example, if a building is required to be designed to LEED gold certification but, during the design, decisions are made that render the building to become LEED silver certified, does the building owner have the right to sue the designer? Is the designer or building owner criminally liable for this shortcoming, and what will be the penalty? Will the building be prohibited from opening as a result?

3.6.5 The Future

A performance-based environmental design method has been developed recently by Task Group 3.6 of the International Federation for Structural Concrete Commission 3.[55] This document is intended for incorporation into existing codes or specifications. It provides general principles applicable to the design, construction, use, maintenance, dismantling, and disposal of concrete structures. It is applicable to both new and existing concrete structures. Performance requirements cover global issues such as generation of GHG and consumption of resources; regional issues such as use and pollution of water and soil; and other issues such as dust, noise, and vibration control. The environmental performance of structures is verified using LCAs.[56] America's first green building code was released by the ICC in February 2009 and contains chapters on green building, planning and design, energy efficiency, water efficiency and conservation, material conservation and resource efficiency, and environmental quality. It is unclear at this point whether the provisions of the "green" code will be incorporated as mandated material into the building code.

Currently, it is up to the building owner to provide for a sustainable structure. As it stands, the purpose of the building code remains the same: to provide a safe building for the occupants. It has not yet been able to incorporate the many aspects of construction that degrade our environment and deplete our precious natural resources. However, the trend is moving in the direction of having building codes address sustainability in some way.

3.7 BROWNFIELD REDEVELOPMENT

Brownfields may be defined as sites that are abandoned, derelict, idled, or underused industrial and commercial facilities where expansion or redevelopment is complicated by real or perceived environmental contamination.[57,58] They are mainly in fully or partly developed urban areas, may require intervention by environmental agencies to bring them back to beneficial use, and have been affected by former uses of the site or surrounding land.

Thus, brownfields are lands previously used for industrial purposes or certain commercial uses, which might have been contaminated by low concentrations of hazardous waste or pollution, but have the potential to be reused once they are cleaned up. Lands that are more severely contaminated and have high concentrations of hazardous waste or pollution may not fall under the classification of brownfields. In contrast to brownfields, *grayfields* are another form of urban property, which may have blighted or obsolete building on land that might not have been contaminated. According to the Congress of New Urbanism, former or declining malls can be classified as grayfields.[2]

Important issues concerned with brownfield redevelopment may include

- Technical identification of the extent and forms of contamination
- Identification of appropriate remediation techniques
- Creation of interactive and inclusive systems of governance and policy making
- Mechanisms to encourage the mobilization of important shareholders such as real-estate developers and local communities

Often, these issues have been dealt with in isolation.[58] An integrated approach is required to develop brownfield redevelopment, involving people working in engineering, construction management, property and real estate, development planning, science, and social science. Support from industry, civic associations, and national and local governments is also required.

Brownfield redevelopment has become an important policy in several developed countries. Virtually every major city within the United States is burdened by brownfields. An estimated 100,000–500,000 brownfields in the United States are abandoned or underutilized. An estimated 64,000 ha of brownfields are in the United Kingdom. Several other countries, such as Canada, the Netherlands, and Germany, also face similar brownfield issues. Brownfields vary in size, location, age, and past use. They can range from a small, abandoned corner gas station to a large former manufacturing plant that has been closed for years. Historically, the contamination of lands and buildings has spawned environmental concerns, discouraging many developers from taking on brownfield redevelopment. The cleanup and development of contaminated lands are further complicated by strict environmental laws.

However, thanks to current economic development and regulatory incentives to support sustainable development, brownfield redevelopment activity is helping to reduce urban decay and reignite growth and investment in local communities throughout the United States. The USEPA began a brownfield redevelopment program during the mid-1990s, giving $200,000 grants to 300 cities and other jurisdictions.

Redevelopment of brownfields into hubs of economic activity will create new jobs and revenues and result in[51]

- Restoring urban property to productive use, thus increasing property values
- Increased job opportunities and local tax revenues
- Improved public health and environment
- Utilization of existing public infrastructure
- Eliminating neighborhood blight, thus improving a community's image and long-term sustainability

The major concern in development is the extent of risk to the public posed by environmental contamination of brownfields. Depending upon the amount and type of contamination, the affected soil may be removed, water may be purified, or concrete or other impermeable layer may be placed on top of the land, and restrictions may be placed on future use of the land. Research is under way to see if some brownfields can be used to grow crops, specifically for the production of biofuels. Many brownfield sites are located in poverty-stricken minority neighborhoods, and hence brownfield redevelopment is an important issue concerning environmental justice. Many brownfield sites are close to urban areas and thoroughfares such as highways and rivers; their reclamation can therefore be a major asset to a city.

Investigation and cleanup of brownfield sites in the United States are largely regulated by state environmental agencies in cooperation with the USEPA. The rules and regulation for cleanup may differ significantly from state to state. The USEPA, together with local and national government, provides technical assistance and some funding for assessment and cleanup of brownfields, as well as tax incentives for cleanup.

Remedial techniques employed to remove contamination may include the following[56,59]:

- Bioremediation (which uses naturally occurring microbes in soils and groundwater)
- In situ oxidation (which uses oxygen or oxidant chemicals to enhance a cleanup)
- Soil vapor extraction (in which vapor from the soil/water is extracted and treated)
- Phytoremediation (in which deep-rooted plants are grown at the site, removed after maturity, and disposed of as hazardous waste because they may have heavy metal contaminants in their tissues)*

Successful brownfield redevelopment requires integrated risk management planning from project conception through construction and cost recovery. Several

* Phytoremediation describes the treatment of environmental problems (bioremediation) through the use of plants that mitigate the environmental problem without the need to excavate the contaminant material and dispose of it elsewhere.

FIGURE 3.18 The Waterfront, the sprawling entertainment, retail, and residential complex in Homestead, Pennsylvania, was once a brownfield. (Courtesy of Matt Freed of the *Post-Gazette*.)

examples of brownfield redevelopment projects have taken place in Pittsburgh, Pennsylvania, where numerous former steel mill sites were successfully converted into high-end residences, shopping centers, and offices. Some of these include the site formerly occupied by Carnegie Steel, which was converted into a successful commercial center called Waterfront, in Homestead, Pennsylvania (Figure 3.18), and a former slag dump for steel mills that was turned into a residential development called Summerset at Frick Park, in Pittsburgh's Squirrel Hill neighborhood.

Yet another category of abandoned lands is *blackfields*, which are abandoned coal and other mines. However, another classification, called *greenfields*, has experienced little or no development activities. Greenfields may also represent agricultural lands and are generally believed, sometimes incorrectly, not to be contaminated.

Comprehensive information about the range of available innovative technologies and technical expertise is available from the USEPA's Brownfields and Land Revitalization Technology Support Center.

The LEED-NC 2.2 building assessment standard provides credit for the use of a brownfield/blackfield as a building site, whereas the proposed LEED-ND provides two points. Even if the site is not officially designated as a brownfield, the credit can be earned if the project team can convince the USEPA and get its willingness in writing to consider the site as a brownfield.[2] According to the ASCE, redevelopment of brownfield sites over the past 5 years generated an estimated 191,338 new jobs and $408 million annually in extra revenues to localities.

3.8 GREEN HIGHWAYS

The rating systems discussed up to now pertain mostly to buildings. Transportation facilities, such as highways in particular, use large quantities of materials in initial construction and during periodic rehabilitation. Recycling industrial by-products and construction materials in highway construction can help generate "green highways" where use of virgin materials and large amounts of energy is avoided. As a part of efforts to mitigate the negative impact of infrastructure, the GHP was developed in 2002. Similar groups have been formed in other countries such as Canada, Brazil, and Norway, in addition to the United States.[60] GHP comprises state and federal agencies (USEPA and USFHA) and an extensive network of environmental, industrial collaborators working toward the development of green surface transportation systems. It is an effort to develop green highways through concepts such as *integrated planning*, *regulatory flexibility*, *community partnering*, and *market-based rewards*, in order to improve safety and functionality. Because the strategies to be used may differ from project to project and location to location, GHP partners have developed the following list of characteristics that apply to green highways[61]:

- Achieve goals through voluntary participation and public/private partnerships
- Provide net increase in environmental functions and values of the watershed
- Exceed minimum standards prescribed in environmental laws and regulations
- Identify and protect cultural and historic landmarks
- Map all resources with a view to identifying and protecting critical resources
- Use innovative and natural methods to reduce and cleanse runoff
- Protect hydrology of wetlands and stream channels
- Maximize use of existing transportation infrastructure by providing multimodel transportation options and promoting public or ride-sharing transportation
- Use recycled materials wherever possible
- Promote the growth of native species and control populations of invasive species
- Promote wildlife corridors and reduce disruptions to ecological processes
- Ensure environmental results by incorporating postproject monitoring
- Encourage smart growth through integration with ecological constraints

To develop a green highway, GHP would take these characteristics, plus many others, into consideration and implement only those that are relevant and feasible for the specific transportation project.

A green highway integrates transportation functionality and ecological sustainability. Three focal points of GHP result in environmental streamlining and stewardship into all aspects of the highway life cycle:

- To build with permeable materials that provide superior storm-water management, thus preventing metals and toxins from leaching into streams and rivers
- To construct with recycled materials, thereby reducing landfill usage
- To design using cutting-edge technologies to protect critical habitats and ecosystems

The technologies that are used by GHP are illustrated in Figure 3.19[61]:

1. *Bioretention*. This process utilizes soils and both woody and herbaceous plants to remove pollutants from storm-water runoff. Runoff from highways is conveyed as sheet flow to the treatment area, which consists of a grass buffer strip, sand bed, ponding area, organic layer or mulch layer, planting soil, and plants.
2. *Porous pavement*. This permeable pavement surface with an underlying stone reservoir temporarily stores surface runoff before infiltrating into the subsoil. Porous pavement helps to recharge groundwater and alleviates flooding and contamination of water bodies (see Chapter 7 of this book/volume for more details).
3. *Environmentally friendly concrete pavement and use of industrial by-products in sub-base and embankments*. Highways constructed from traditional concrete leach toxins into the surrounding ecosystems. Coal combustion products such as fly ash, blast furnace slag, reclaimed pavement materials, and many other industrial waste materials are used as highway construction materials. Use of such industrial by-products can save virgin resources, reduce energy consumption and GHG emissions, and reduce the need for landfill space and new landfills.[60] In addition, foundry by-products such as foundry sand and foundry slag are used increasingly in highway embankments, retaining wall backfills, sub-base for pavements, and hydraulic barrier layers.[60] Shredded tires are also used as backfill in earthen structures, embankment over soft ground, or backfill behind retaining structures. However, unlike with natural earthen materials, caution should be exercised when using by-products, and their potential for pollution should be assessed in the context of the given environment and application.[60]
4. *Development of riparian forest buffers*. These buffers play an important role in maintaining the health of watersheds. They are areas of forested

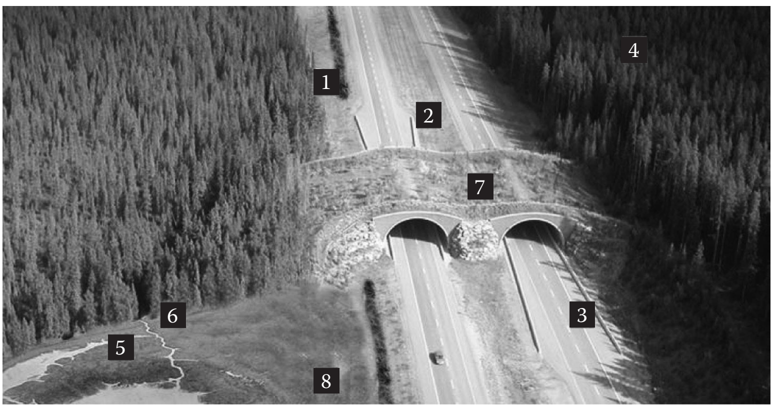


FIGURE 3.19 Technologies involved in green highways. (From http://www.greenhighways.org; accessed July 10, 2009. Courtesy of Tony Clevenger.)

land adjacent to streams, rivers, marshes, or shoreline and form the transition between land and water environments. Riparian forest buffers not only improve water quality but also provide habitat for wildlife and fish.

5. *Wetland restoration by passive or active approaches.* Passive approaches can be adopted when the site under consideration still retains basic wetland characteristics, and the source of the degradation can be stopped. However, when a wetland is severely degraded, active methods such as recontouring a site to the desired topography, changing the water flow using water-control structures (such as weirs or culverts), intensive planting and seeding, intensive nonnative species control, and bringing soils to the site to provide the proper substrate for native species have to be adopted. Active methods may be time consuming and expensive.
6. *Stream restoration.* To halt the activities causing degradation of the ecosystem is the first and most critical step in implementing restoration. Restoration actions may be passive (e.g., attenuation of chronic disturbance activities) or active (intervention and installation of measures to repair damages).
7. *Development of wildlife crossings.* Wildlife crossings have been developed as a solution to minimize the death of millions of birds, reptiles, mammals, and amphibians and to reduce animal–vehicle collisions. These bridges, culverts, tunnels, and barriers redirect animals over, under, or around the highway and greatly reduce the risk of vehicular collision.
8. *Soil amendments.* Compared to compacted, unamended soils, amended soils provide greater infiltration and subsurface storage and thereby help to reduce a site's overall runoff volume, thus helping to maintain the predevelopment peak discharge rate and timing.

3.9 CASE STUDIES

Several examples can be cited for the successful implementation of sustainability principles; a few outstanding case studies are presented here.

3.9.1 Symphony Tower, Atlanta

This 41-story, 196.5-m-tall, 62,245-m^2 reinforced concrete office tower, located in the heart of midtown Atlanta, Georgia (1180 Peachtree, also known as the Symphony Tower), was designed by Pickard Chilton Architects (structural engineer: Thornton Tomasetti Engineers, NY) and was completed in February 2006. It is the first high-rise office building in the world to be precertified for silver status in the LEED Core and Shell Development and the second to be awarded LEED-CS Gold status, satisfying more than 30 green and high-performance requirements (see Figure 3.20a). The property offers several sustainable design strategies:

- High-performance glass enclosure with projected vertical mullions to mitigate solar gain
- Natural-light photometric sensors to reduce perimeter artificial lighting

(a) (b)

FIGURE 3.20 Two LEED-certified concrete buildings: (a) the 41-story reinforced concrete office tower in Atlanta; (b) CII—Sohrabji Godrej Green Business Centre, Hyderabad, India.

- Unique water management system using captured and stored storm water and condensate from the building's mechanical system to provide 100% of the project's irrigation water
- Highly efficient heating, ventilation, and air-conditioning (HVAC) systems in which outside air delivered via the preconditioned air system is measured and controlled in air-monitoring stations with changeable set points
- A non-accessible green roof at the 18th level and a shading veil on the 41st level roof to reduce the heat island effect
- Mechanical systems capable of controlling humidity levels, which control mold and mildew
- Incorporation of recycled materials and the use of certified woods

3.9.2 Sohrabji Godrej Green Business Centre, Hyderabad, India

The CII Sohrabji Godrej Green Business Centre, Hyderabad, India, designed by Indian architect Karan Grover, received the prestigious "platinum" rating from the USGBC in 2003. This was the first platinum-rated green building outside the United States and the first in India (see Figure 3.20b). The sustainable features of this building are presented here[62]:

- This 1900-m^2 building has a courtyard, meant for cultural functions, that provides for light and climate control. All enclosed spaces are coupled with smaller open courts encircling this larger courtyard. These courtyards act as "light wells" illuminating adjacent work areas.

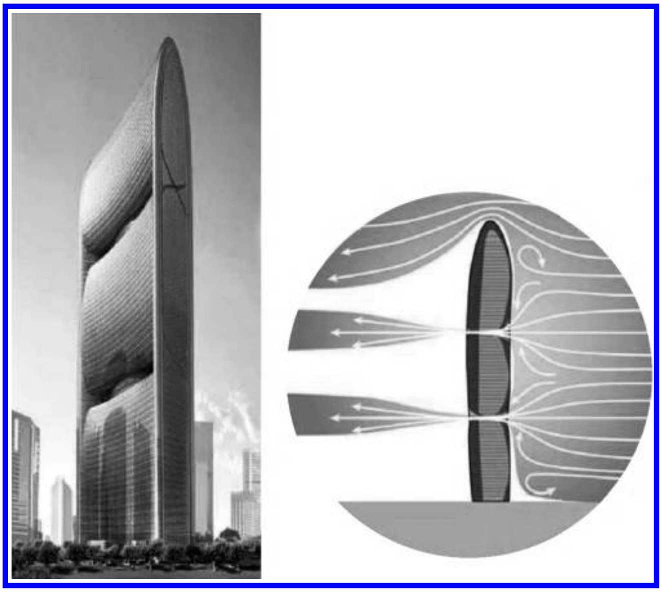
- Sensors and dimmers are used to control the illumination levels automatically. In addition, traditional *jali*, or lattice wall, is used for the efficient use of natural light. With these features, a lighting energy savings of 88% is achieved compared to an electrically lit building of the same size.
- A rooftop grid of solar photovoltaic cells provides approximately 24 kW or about 16% of the building's electricity needs. Two wind towers and a heavily insulated roof further reduce the cooling load.
- Water conservation measures include provision of permeable pavements and a water pond recycling wastewater using root-zone treatment, which uses specially selected plants and weeds as filters, and use of low-flush toilets and waterless urinals.
- The building is located near a public transportation station, has facilities for bicycle riders, and uses electrically driven cars. The design, siting, and construction documented a 62% reduction of CO_2 and other GHGs.
- Approximately 66% (by cost) of the material was sourced within a radius of 500 mi. Of this, 95% of the raw material was extracted or harvested locally. Of the building materials, 77% used recycled content in the form of fly ash, broken glass, broken tiles, recycled paper, recycled aluminum, cinder from industrial furnaces, bagasse, mineral fibers, cellulose fibers, and quarry dust.
- The building reused a significant amount of material salvaged from other construction sites. A waste management plan ensured that 96% of construction waste was recycled.

The Wipro Technologies Development Center in Gurgaon, India, is the largest platinum-rated green building in Asia that has been commended by the USGBC. The new assembly building in Chennai has become the first assembly building in the world to be designed and constructed as a green building and has received gold certification from the Indian GBC.

3.9.3 Pearl River Tower, China

The 71-story, 309.6-m-tall Pearl River Tower, in Guangzhou, China, has been designed as the most energy efficient of the entire world's super-tall structures; it has a footprint of 214,100 m^2 and was completed in 2011. Designed by Skidmore, Owings & Merrill LLP (SOM) of Chicago, it is expected to consume approximately 58% less energy than a traditional structure of the same size and to serve as a model for future carbon-neutral towers.[63] The tower features both active and passive approaches to limiting carbon emissions through new technologies.

The building's form guides wind to a pair of 6 × 6.8-m-size openings at levels 24 and 48. The wind flowing through the openings helps drive vertical-axis wind turbines that generate energy required for the HVAC systems. The openings also function as pressure relief valves by allowing wind to pass through the building instead of applying pressure on it (see Figure 3.21). Thus, the wind loads on the building are reduced. The facades have been designed to decrease the drag forces and optimize the wind velocity flowing through these openings. Note that in contrast to the normal



(a) (b)

FIGURE 3.21 Zero-energy Pearl River Tower in Guangzhou, China. (a) Architect's image; (b) wind passing through tower, reducing the wind pressure on the tower. (From http://www.som.com.)

practice of placing the narrower sides pointing toward the prevailing wind, the broad sides of the building are aligned perpendicular to the prevailing winds to harness the wind power.

The building has been designed to generate enough renewable power to meet its energy demands by using wind and solar energies and by reusing the generated energy. This is done by the following methodologies[63]:

- Orienting the building to take advantage of midday sun, the north- and south-side facades are internally ventilated by a high-performance, active, and double-glazed wall system; the east- and west-side walls are provided with triple-glazed facades. The south-side facade reduces heat gain, which leads to less demand on the HVAC systems.
- Energy is reclaimed by routing each floor's exhaust air into the south side's double-layer curtain–wall cavity. This thermal barrier of hot, dry air can then be reused on the mechanical floor for passive dehumidification.
- A chilled slab-concrete vaulted ceiling system cools the air drifting up from the underfloor ventilation system, and the thermal mass of the concrete is used for energy storage. This system reduces energy used for cooling by 40% compared to a conventional HVAC system.
- A geothermal heat sink is used to provide cooling water, reducing the size of the mechanical plant by about 30%.

- Maximizing the use of natural lighting through controls that respond to light and integrating into a system of automated blinds, the building uses a low-energy, high-efficiency lighting system.
- To achieve the final goal of net zero energy, the design team incorporated three power-generating technologies: wind, integrated photovoltaic cells, and microturbines.

As mentioned, the tower's curvilinear structure helps force air through four turbine inlets in the facade to activate the turbines. These are estimated to produce nearly 15 times more electricity than a typical stand-alone wind generator. Solar photovoltaic cells, located in an asymmetrical arrangement at the roof level, provide electricity as well as function as a solar shade to fend off the negative effects of direct solar radiation. The building envelope also contains photovoltaic cells. Microturbines will not be installed until the Guangzhou utility decides to connect them to the local electric grid so that the excess energy generated can be transferred and sold to the city's electric grid.

It is of interest to note that SOM is in the process of designing and constructing more than 30 projects involving sustainable design, including 7 World Trade Center, New York; the Chicago 2016 Olympic Master Plan; the 56-story Jinao Tower, China; and the US Census Bureau Headquarters, Suitland, Maryland.

Recently, Leung and Weismantle conducted a hypothetical investigation on the energy consumption of residential buildings similar in height to that of Burj Khalifa (about 1 km) and situated in Dubai.[64] Their study revealed that environmental variations with altitude, such as reduction in air temperature, pressure, and humidity with increased height, can significantly contribute to the sustainability of tall buildings. Using the midlevel floor of Burj Khalifa as an example, they showed that the total cooling load reduction at summer peak design hours can be as much as 11% by just including temperature and air density variations.

3.10 SUMMARY

Our planet is at peril due to a number of factors, including population explosion, urbanization, excessive energy use and associated global warming, water scarcity, and inefficient waste management. A number of solutions have been proposed for sustainability. A few of the sustainable solutions are discussed. The construction industry consumes 40% of the total energy and about one-half of the world's major resources. Hence, it is imperative to regulate the use of materials and energy in this industry. Green building rating systems such as LEED and Green Globes certification have been evolved for sustainability of the construction industry. Life cycle costing and life cycle management of resources play an important role in the development of sustainable construction. However, unless the means of making these green buildings affordable for the common man are developed, we cannot attain full sustainability.

A truly green building should be energy efficient, incorporate concrete that contains the least amount of Portland cement, and use large volumes of supplementary cementitious materials and recycled aggregates. Sustainable construction also requires the conversion of brownfields into construction sites; it is imperative to apply sustainability concepts not only to buildings but also to other infrastructure developments. In this respect, the development of GHP should be recognized and appreciated. The emergence of "zero-energy" buildings and sustainable structures will reduce dependence on fossil fuels, which is the main cause of global warming.

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4 Sustainability through Thermal Mass of Concrete

William Juhl

CONTENTS

4.1 INTRODUCTION

The achievement of sustainability in the construction of conditioned buildings inherently mandates consideration of the effect of thermal mass. The thermal mass of the aggregate construction materials allows the structure to absorb, store, and release significant amounts of heat affecting, often substantially, the net energy balance and consumption for the structure. Structures that have been built of concrete and masonry for decades have shown these advantages because of their inherent thermal mass. Absorption and retention of energy for periods of time reduce energy consumption by transferring heat in a natural cycle through a thermal mass building component. The heating and cooling cycles are balanced since mass slows the response time and reduces temperature fluctuations. *Effectively, thermal mass enables time transport of heat energy.* In addition, a massive building uses less energy than a similar one with lower mass due to the reduced heat transfer through the massive elements as a natural phenomenon. A natural result of these two facts is to shift energy demand to off-peak time periods, generally at lower costs. This is obvious since power plants are designed to provide power at peak loads; the peak load consumption is reduced, optimizing the energy usage and sustainability from this perspective.

This chapter deals mainly with the material and construction aspect of sustainability through thermal mass as a basic quality of concrete (and masonry) in structures. It also considers the progression of the use of thermal mass in construction—perhaps in the wrong direction of energy conservation.

4.2 THERMAL MASS AND ENERGY-EFFICIENT BUILDING SYSTEMS

Early humans sought shelter in caves where dwellers were partially protected from the elements. The protection or isolation from the elements included physical protection, moisture, and mediation of temperature variation. In addition to the restriction of convective air movement, a predominant element of caves that mediated temperature variation was the thermal mass of the earth and rocks of the cave. Stone, earthen, and, later, masonry structures emulated part of that inherently temperature-stable environment. Subsequently, heavy timber and log homes also included thermal mass to a certain degree as an element of their thermal performance.

With the arrival of the industrial age and relatively inexpensive and abundant fuel sources, speed of construction combined with exploiting readily available timber became the driving factor in North American construction. Thermal mass as an essential element of dwelling shelter was largely forgotten, and light frame 2 × 4 in. timber cavity walls became the dominant form of construction in residential and low-rise construction. Temperature control in the heating season was achieved by burning more wood, coal, oil, and gas. Southern states of the United States languished in population growth until the widespread introduction of air conditioning in the 1960s that, again by consumption of fuel to produce electricity, overcame the inherent deficiencies of light frame construction. Lessons learned in prior years of high thermal mass structures and designing for flow through natural air circulation were essentially forgotten by the magic of mechanically cooled air. Achieving more temperate living conditions then became possible with the consumption of significant electric power, with portions thereof generated by fossil fuel consumption.

Little attention was paid to the energy efficiency of buildings until the energy crises of the 1970s. Cast-in-place (CIP) concrete historically found limited use in residential construction with the exception of areas such as tropical environments with both extreme weather situations and destructive insect threats. While it was appreciated that concrete had value, the great obstacles were cost of construction due to the labor and material for forms consumed and subsequently discarded, the associated problems with attaching claddings and installing utilities, and the issues of integrating insulation along with the concrete of the walls.

On the European continent, however, in the aftermath of World War II, a different environment existed—in part as a consequence of relatively scarce timber resources and a historic and traditional valuing of long-term multigenerational durability of structures. A substantial interest arose in developing building materials that incorporated both structure and insulation into the same product while simultaneously employing scrap or recycled materials in part. The earliest experiments involved combining Portland cement with crushed wood fibers and recycled aggregate resulting in products with higher resistance to thermal transfer than standard concrete. Derivatives of these early products with special-purpose uses, particularly in sound control, are still found.

4.3 CONCRETE WALL SYSTEMS

Concrete wall systems vary in different ways to make energy-efficient but structurally sound walls for exterior application in residential homes. They are typically standard 8 ft. high or higher depending on the architectural design. The walls are most commonly reinforced with grade 60 steel reinforcing bars depending on the structural design. The nominal compressive strength of the concrete used in these wall panels varies from 2500 to 4000 psi. Very little finishing is required externally; it can be treated as a conventional wall, and any exterior or interior finishing can be applied without extra effort.

4.3.1 Precast Concrete

Precast/prestressed concrete can contribute to sustainable design in many ways. It is a versatile, durable material produced in a factory by highly trained personnel, with virtually no waste, under stringent quality control measures. Precast panels can be quickly erected on the job site with minimal disruption to the site, and precast concrete's thermal mass can save energy and increase comfort. It has been used for more than 50 years in the building industry with success and some sustainability principles already embedded in the system.

The use of precast concrete systems for residential construction has enjoyed some success, but overall use has been limited primarily to employment within tropical zones where environmental conditions are harsh, and concrete walls and roofs provide the only durable remedy. In addition to termite issues, the major threat that can be largely resolved with concrete is mitigation of damage due to high winds, particularly hurricanes, typhoons, and tropical cyclones. One such notable employment of precast concrete was the Dededo Homes project completed by Kaiser in the early 1960s on the island of Guam (see Figure 4.1).

External walls and roofs were precast using non-insulated concrete and were successful in withstanding several devastating typhoons in subsequent years. Limiting the employment of precast in residential buildings has been the need for substantial scale of the construction, coupled with relatively simple structural design. While precast has been proven to be economically feasible, such a deployment mandates a substantial scale project of nearly identical homes. Since the conclusion of the successful Guam Dededo project, experience has suggested that this remains a significant barrier to widespread adoption. Notably, the homes of the Dededo project were never intended to be mechanically cooled and were entirely non-insulated. Their design relied on the cooling enabled by the daily diurnal temperature variation combined with natural flow through ventilation and high thermal mass to provide indoor climate modification.

FIGURE 4.1 A typical house design that was constructed in Guam. Nearly 40 years after their initial construction, the homes have demonstrated an excellent record of disaster performance, and over 6000 such homes have been constructed. (From Warnes, C. E., Disaster-resistant shell houses, *Concrete International*, 30: 39–43, 2008.)

Like all manufactured products, the production and use of precast concrete building systems impose environmental demands. Precast concrete offers a competitive building solution based first on cost, long-term economic benefits, energy efficiency, lower maintenance, and overall operating costs as well as opportunities for future reuse when the occupancy of a building changes. Precast concrete offers a dramatic range of colors and finishes and unlimited design possibilities that are difficult to match with any other material, while creating structures that can provide superior environmental and energy performance from a life-cycle perspective. After analysis of the precast concrete system from the sustainability point of view, it was observed, in 2010, that the precast concrete industry has made great strides, as illustrated through the reduction of use of coal, natural gas, etc. It is claimed that this amounted to approximately 30% in the last four decades. The data indicate a 10% decrease in direct emissions of CO_2 per tonne of concrete product between 1990 and 2010. Energy efficiency has been improved in the last two decades by more than 15%.

4.3.2 CIP Concrete Systems

The use of traditional CIP concrete in residential building has been limited. In the few instances of its use, employment of CIP has been due to special circumstances driving decisions toward concrete. Residential structures are typified by substantial variability. This variability in having many and varied fenestrations, wall segments of varying lengths, and, in many cases, heights, and sloped foundations produces issues that substantially increase the cost of a residential structure if traditional site-constructed and removable-form systems are used. Both material costs and labor are a significant time and cost issue. Additionally, to provide required insulation, added frame members are required on the inside of the concrete walls along with insulation, vapor barrier, and, typically, employment of conduit for electrical wiring. Thus, CIP by conventional forming methods is essentially not cost competitive with traditional framing for residential construction.

4.3.2.1 Insulating Concrete Form Systems

A subset of CIP is a notable exception that has been gaining acceptance in residential construction across North America. Originating first in Europe in the 1960s and then migrating to eastern Canada and the northeastern United States was a variation on traditional CIP that provided for forms that were multipurpose and that stayed in place after the walls were poured. Called insulating concrete forms (ICFs), this class of product was designed as a stay-in-place form for poured concrete that was made predominantly of expanded polystyrene (EPS), a polymer product derivative of oil and natural gas refining. In each case, the objective was to combine the insulation derived from thermal resistance of the EPS with the thermal mass and structural value of the concrete and further to minimize infiltration by creating a monolithic wall system.

The earliest ICFs used sheet EPS connected by plastic or metal clips or were molded EPS that imitated the form factor of concrete masonry unit blocks. In the latter case, the form factor of the concrete grout was a grid-shaped pattern. This pattern had the downside effect of having areas between the post and beams in which there was no solid material at all (only EPS foam) that was subject to potential penetration. Also, due to the square grid structure, there was limited inherent in-plane shear resistance (see Figure 4.2).

In an effort to incorporate enhanced shear values and provide a solid concrete envelope, the next evolution resulted in grid shapes with infill in between the webs. Called a "waffle grid" system, it proposed to resolve some of the issues of the post and beam structure. However, in practice, there were difficulties in assuring proper placement of the concrete without significant voids. And the slender cavities, even when properly filled, provided limited shear resistance. In active seismic zones or potential high wind zones, there were concerns about durability.

As enhancements in the chemistry and manufacture of plastics occurred that facilitated improvements in durability and utility of plastic connectors (typically polystyrene), the response to these issues was to design ICFs that provided for a uniform flat concrete wall sandwiched between two panels of EPS that were held together by polystyrene connectors, typically called "webs" (see Figure 4.3). These flat-wall systems began to emerge in the 1970s and are the predominant systems today. Characteristically, they have a uniform concrete section of 4–12 in. or more

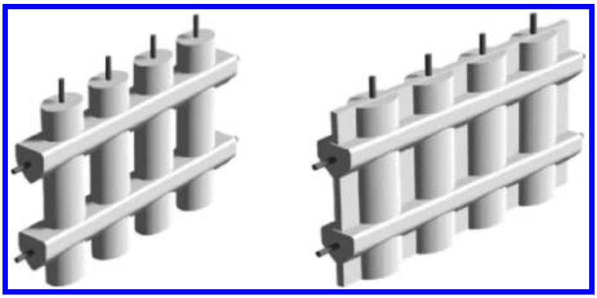

FIGURE 4.2 Typical early ICF systems. (Courtesy of Portland Cement Association.)

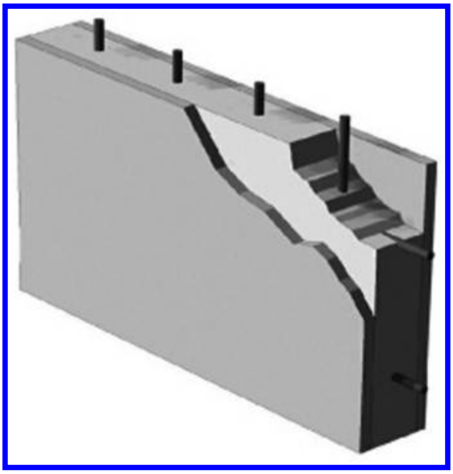

FIGURE 4.3 A state-of-the-art ICF concrete flat wall system. (Courtesy of Portland Cement Association.)

of steel-reinforced concrete, sandwiched between two layers of EPS foam averaging about 5 in. in total thickness. The thermal resistance (*R*-value) of the assembly is chiefly derived from the EPS foam.

Today's typical ICF building system is an intelligent building product that combines an array of functions into a relatively simple and easy-to-use module. These forms are characterized by the following:

- They provide the form to contain concrete during placement.
- The form stays in place afterward and reduces form waste to the 1%–4% range.
- They employ a module size (typically 48 in. long × 16 or 24 in. tall) that is readily managed manually without requiring lifting equipment.
- Connectors or webs are molded in place in manufacturing and are typically modern durable polystyrene plastics that are UV resistant.
- These connectors are spaced 6–8 in. apart in the horizontal plane and have additional function in providing clips or fingers that secure the reinforcing steel.
- Additionally, virtually all flat-wall ICFs have embedded furring strips into which fasteners (typically screws) are inserted for attaching interior and exterior claddings.
- Because the EPS insulation is continuous throughout the wall (except at window and door openings), the thermal resistance of the wall assembly (commonly R-24+) is uniform.
- The wall system provides both an air barrier and a vapor barrier as an inherent element of its design (a *weather-resistant* external barrier may still be required).
- An average ICF wall provides acoustic separation across its boundary that is significant and always sensible to the occupants.

- The foam is removed in channels to provide chases to install electric or plumbing utilities, eliminating, at least in residential applications, the need to use conduit.

There are numerous benefits that accrue within the domain of construction with ICF systems:

- *Durability.* ICF is, at its core, standard Portland cement-based, steel-reinforced concrete. The temporal and structural durability of CIP concrete is well known and is lacking in mystery and risk. When encapsulated between the concrete and a cladding and protected from UV and physical damage, the EPS foam has durability projected to be similar to that of concrete. An ICF structure arguably is a 200- to 500-year durable building *without a requirement for structural modification*.
- *Practicality.* ICF construction can readily be introduced to and undertaken by any number of the building trades. It requires less specialized training and accumulated skill than most other forms of construction that can be used for building efficient envelopes. James Dillingham, PE, D&Z Engineering, Shingle Springs, California, says,

  > I know of no other construction methodology for external envelopes that can be done with the same assurance of success on the first project as is the case with ICF. I am very comfortable with recommending it to first-time contractors or reasonably prudent owner–builders. I would not endorse any other building system in this way.

  In its design, ICF accommodates readily the subsequent trades that finish out the structure (electricians, plumbers, sheet rockers, plasterers, finish carpenters, etc.) with minimal change in their installation practices from working in frame construction. Specialty tools and equipment are not required. Importantly, it is an advanced building system that is fundamentally practical to deploy broadly across the entire spectrum of construction in North America.
- *Scalability.* Conveniently, ICF modules are manually manageable without the requirement for mechanical devices for placement. As such, ICF works effectively across projects of virtually any scale, from 100-ft.^{2} kiosks to 23-story high rises and everything in between.
- *Risk management.* The construction world is one in which risk management is a significant element of the practice. ICF walls, with concrete as their core, are in their nature a reduced-risk material with which to work. Assuming proper concrete mix design and proper placement, the long-term behavior of an ICF wall can be well evaluated. Mold and mildew, biodegradation, and other processes that affect frame walls constructed with organic materials have essentially no effect on ICF.
- *Geographic and climate zone applicability.* ICF construction works famously across virtually all climatic environs. From Fairbanks, Alaska, to Miami, Florida, and from San Diego, California, to Portland, Maine, in all cases, ICF contributes significantly to the effectiveness of the structures. In

some areas, the primary benefit is reduced energy requirements; in others, it is enhanced safety, and in others, its temporal durability is a key factor. ICF can be used anywhere, and, although variable, it returns a value that exceeds that of conventional frame structures.

- *Hazard protection.* Across North America, there are multiple natural hazards for which historic construction practices have provided, at best, limited protection. These include tropical storms, hurricanes, tornadoes, wildfires, and earthquakes. Construction with ICF can substantially mitigate, or, in some cases, largely eliminate occupant risk from these hazards. (For example, by the inclusion of a concrete roof system [ICF or otherwise], a residence can be built to withstand the wind forces of a Fujita 5 tornado.)
- *Realized energy savings.* While dependent upon climate zone, specific design, and the operating behavior of occupants, in broad strokes, ICF homes realize a 30%–50% reduction in the consumption of fuels to provide climate control within the structure. When combined with additional building practices and systems, the reduction can be 60%–80% less than that of a comparable frame structure.
- *Cost of construction.* ICF approaches the cost of conventional frame construction. The major factors of cost between ICF and frame construction are experience of the installation crew and the sensitivity of the design relative to the construction methodology. Design–build firms that are experienced in ICF construction as of 2010 are bidding residential projects at the same price for ICF as that for well-insulated 2 × 6 in. frame construction. As ICF becomes more widespread, it is anticipated that broad parity with frame construction will occur. Over the next decade, building codes will be continuing the shift toward requiring greater energy efficiency. In that enhanced environment, it is a near certainty that ICF construction will become one of the more cost-effective means of achieving these future standards.

4.4 DESIGN OF A CONCRETE WALL SYSTEM

Designing residential structures employing concrete walls for the external envelope requires only a modest departure from frame construction design processes. From an architectural viewpoint, the major issue is to recognize the thicker walls, which are typically 11–13 in. (e.g., using typical ICF systems). The other architectural issue to be recognized is that upper story concrete walls require their load to be borne by an inline concrete wall below or by a beam of either structural steel or cast concrete. An upper level concrete wall cannot be permanently supported on a wood beam, and this is a departure from wood-frame design; in some cases, this fact is not initially realized by architects who are practiced in wood-frame construction.

Concrete walls using ICF systems, however, add design flexibilities when compared to traditional frame construction. For example, energy codes place limits on the extent of glazing that can be employed in many houses. ICF external walls, when compared to traditional wood-frame walls, provide a significantly higher thermal performance of the wall as an assembly; as a consequence, larger glazing surfaces can be incorporated within a design and still successfully meet the requirements of increasingly stringent energy codes. Concrete wall systems also inherently incorporate high shear resistance. This eliminates much of the supplemental steel, moment frames, shear panels, etc., that are increasingly required in light frame construction, particularly in areas requiring accommodation of high seismic or wind loads. To the architect designing for seismically active areas, this inherent capacity allows more flexible design with regard to the placement and size of window and door openings.

From the structural engineering viewpoint, the use of concrete in the external walls poses little challenge. In a departure from frame construction, all required shear resistance is typically acquired in the external walls, thus frequently eliminating the requirement for internal shear walls and eliminating most or all requirements for supplemental steel members to provide the structural stiffness to meet shear requirements. One obstacle sometimes observed is that some structural engineers who are practiced in structural concrete design are not similarly experienced in a hybrid structure that also employs wood frame. Concrete residential structures typically are such hybrid systems that use wood-frame elements in internal walls, elevated floors, wooden roof members, and, in some cases, some of the external walls to be constructed out of wood also. This marriage of concrete and wood structures comes together in ICF construction.

In the quest toward sustainability, one element largely overlooked in contemporary North American residential design is long-term durability: measuring the net effect on the environment of a residential structure from a multigenerational time frame. Enlightened building science needs to evaluate the effectiveness of these concepts against a broad grid of considerations—among them, long-term durability, effectiveness in varying climate zones, and the practicality of introduction into the historical construction process. In general, high thermal mass concrete construction stands up very effectively when measured against such broad spectra of considerations.

4.5 ENERGY EXCHANGE

The energy exchange of a building with its exterior environment is governed chiefly by three elements: thermal transfer through the envelope walls by (1) conductive or radiant heat transfer, (2) infiltration or air movement (convective), and (3) the inherent thermal mass of the structure. Control of infiltration and thermal resistance are the beginning of the process, and the employment of thermal mass realizes the full potential of the earth and sun to minimize the consumption of energy to stabilize temperature.

Energy transfer from buildings is inherently bidirectional and dependent on the direction of the thermal gradient. The three sources of external energy that affect a structure are the sun (radiant), air molecules themselves (convective and conductive), and the earth (conductive) upon which the structure rests or is embedded. With the exception of the subsoil temperatures, the other sources vary substantially in their effect throughout the 24 h of the day. Radiant heat transfers inward during the day, becomes neutral at dusk, and then typically transfers outward during the dark. It is a similar situation with conductive transfer to and from the air molecules. Energy transfer with regard to the earth is essentially a constant heat sink that has varying effects on the structure that are dependent on interior temperatures and the seasons.

The transport of heat energy into or out of a structure is affected by all of the preceding items. Hopefully, it is quite obvious that air molecules entering or exiting a structure carry with them heat energy. Controlling such heat energy transport in its very nature then requires control of movement of the air molecules. The emphasis is on "control" rather than elimination. A structure that is relatively airtight provides the foundation and precondition necessary to enable systems to be employed to control the exchange of air and moisture between the interior and exterior environments. The concept of placing a positive value on the feature of wood-frame houses that they "breathe" is an illusory value. Such air leakage, while it allows blending of air between the interior and exterior of a structure (with an assumed moderation of potentially undesirable moisture, gases, or particulates), in effect represents an unregulated transference of energy. Leaking air into or out of a structure is an uncontrollable transport with associated negative consequences.

A relatively airtight environment creates the situation to enable designers and builders to control and manage the exchange of air, moisture, and particulate matter. This is a somewhat new mandate to builders and designers. Broadly speaking, this has been addressed only sparingly in history and, in many cases, entirely ignored. This is particularly critical in climate areas of high humidity and high temperatures, where moisture control is very critical. The management of air quality will be increasingly important and is an integral element of design adequacy as more energy-efficient and low-infiltration homes are built.

> The synergy of higher R-value, virtually no air *infiltration*, and thermal mass in ICF assemblies results in performance that simply can't be duplicated with traditional frame assemblies.
>
> **David Shepherd**
> *AIA, Director of Sustainability, Portland Cement Association (PCA)*

Throughout the 24 h of each day, substantial changes occur in exterior temperature and available energy (see Figure 4.4). Since the earliest times, shelters have sought to manage those sensible changes to create a more comfortable ambient environment for human occupancy. The holy grail of advanced building technology from an energy balance point of view would be to construct a passive structure that neither consumes nonrenewable resources nor emits exhaust products. Artful use of the three elements can approach this reality.

Thermal mass has a role in this that was appreciated historically but has been somewhat eclipsed in modern building techniques. Thermal mass provides the designer with a method of storage of heat energy. Once stored, the energy can then be released subsequently to heat or as an element of design that serves to cool. From a mechanical point of view, thermal mass can be envisioned as analogous to a flywheel. This thermal mass effect can be used to great effect to store excess heat (typically accumulated in the daylight hours from various sources) and then either venting it at night by expelling the heat into cooler air or retaining it within the

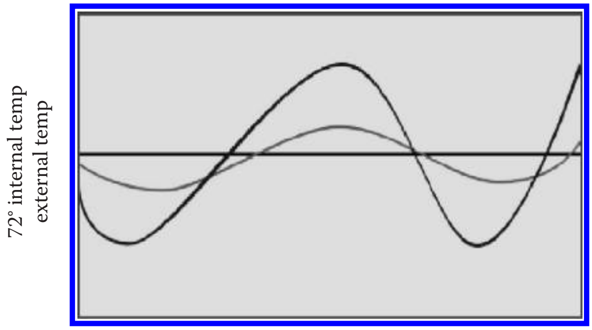

FIGURE 4.4 The insulated concrete form efficiency in a 24-h cycle. (Courtesy of Insulating Concrete Form Association.)

structure. This process, called heat flow reversal, reduces or eliminates the need for energy input from active energy sources.

ICF systems incorporate a blending of all three elements of energy-efficient envelopes: controlled infiltration, relatively high thermal resistance (R-22+), and a contribution to thermal mass due to the concrete within the wall assembly. The practical effect in summer heating is that an ICF structure that has been precooled by nighttime ventilation will shift the maximum temperature rise within the structure to a later time in the day. This delay in temperature rise is dependent upon many variables but tends to be on the order of 2–3 h in hot climate conditions. This time shift often forestalls the need for mechanical air conditioning or reduces the run time requirement.

In a heating scenario, ICF walls provide additional thermal mass that is particularly effective to enhance a passive solar design. When coupled with appropriate orientation, exposure, roof overhang, and a concrete slab or floor system of substantial thermal mass, this energy flywheel greatly mitigates the requirement for supplemental energy consumption for heating.

ICF construction, although still a small segment, has nonetheless entered the mainstream of construction practices. High-rises to custom homes to production developments are all being built using ICF today. ICF continues to grow in market acceptance as it is appreciated for its values in energy efficiency, durability, and safety and its adaptability by the conventional construction trades. At its core, it is simply CIP flat-wall steel-reinforced concrete, a long and well-understood construction medium. The relative magic of ICF is that it is a deployable system that addresses a broad range of requirements and provides the energy resource reduction that will be a hallmark of twenty-first century building standards.

4.6 DESIGN OF ENERGY SYSTEM IN THERMAL WALLS

As stated earlier and demonstrated by testing their suitability, insulated concrete walls are efficient due to their thermal mass. However, to maintain some standard practice, testing was done as government-sponsored research by the National Association of Housing and Buildings[1] in which all aspects of design of heating, ventilating, and air-conditioning (HVAC) system designs are illustrated. The objective of this work was to compile available information regarding energy use in concrete homes, develop additional information as needed, and use it to develop a methodology to size HVAC equipment properly for concrete homes in the United States and Canada.

The mass of concrete also provides excellent acoustic insulating properties for airborne sound. This makes concrete ideal for external walls in buildings facing roads with heavy traffic and as insulation between different areas in a building. Precast concrete panels are often used as noise barriers beside roads and railroads.

4.7 RESIDENTIAL CASE STUDY (ANECDOTAL)

The 4600-ft.^{2} home shown in Figure 4.5 was constructed in 2001 in the California Sierra Nevada foothills using all ICF walls from foundation to top plate. It has been in part a living laboratory. The lower level is a full basement exposed to daylight on two sides. The exterior walls were done using the Amvic Building System ICF block, which is typical of the "best-of-breed" modern ICF systems available on the market today. The walls have 6 in. of flat-wall steel-reinforced concrete at their core, 2.5 in. of EPS foam on each side of the concrete core, sheetrock as the interior finish, and either fiber cement shingles or Portland cement-based stucco as the outer cladding. The composite wall has a tested thermal resistance exceeding an R-24. Unlike frame structures, however, the walls have continuous insulations with no thermal bridging other than around the windows and doors. The roof is framed with wooden trusses, and the attic space is conventionally insulated with R-36 fiberglass.

Located at a 2500-ft elevation facing westward in the Sierra Nevada, the home has been tested by a wide range of weather and climate. Seasonal variations occur

FIGURE 4.5 An all-ICF home in California's Sierra Nevada foothills. (Author's photo.)

from the low 20°F to over 105°F in midsummer. Passive solar principles were incorporated in the design, with moderate south-facing glazing and interior hard surface high thermal mass flooring. Roof overhangs and deciduous trees shade the south glazing in summer while fully exposing it in winter. The R-24 walls, high thermal mass, and low infiltration result in greatly reduced energy requirements compared to other structures of similar size.

Experimentation on multiple occasions over the seven seasons after completion verified the owners' performance expectations of the ICF system. For example, in the January–February time frame, the owners have run experiments to explore the effect. Over periods up to 5 days' duration, under conditions when morning minimum temperatures are around the freezing mark, and the days are sunny and warming to the upper 50°F in the afternoon, the home will float between the low 60°F and 70°F, *without running the furnace or fireplace*. The morning minimum temperature that the house will drop to is 63°F or 64°F on the upper level and 64°F or 65°F on the lower level. This thermal performance relies chiefly on the capture of heat energy by solar gain during the day and its storage in the thermal mass of the structure. Additional heat sources from normal human activity also serve as moderate heat sources, including heat generated by lighting, appliances, cooking, body heat, etc.

Figure 4.6 illustrates the demonstrated temperature range: 29.6°F outside and 64.9°F inside. Note that this photo captured the temperature approximately more than 3 h *after* the minimum temperature of the day, when it was several degrees colder.

The home is located in a rural, tree-covered area with abundant hardwood fuel sources. The owners have found that throughout the winter, the furnace can be left turned off by using the efficient fireplace with two or three loads of firewood per day, which is sufficient to maintain the temperature around the 70°F mark (see Figure 4.7). Note that the fireplace, hearth, and wood box are natural heavy stones, which adds further thermal mass to the structure.

FIGURE 4.6 Interior and exterior temperatures, 10:34 a.m. mid-February 2006 in the California foothills at 2400-ft. elevation.

FIGURE 4.7 Efficient fireplace system that successfully heats a 4600-ft.^{2} ICF home in winter. (Author's photo.)

Summertime performance is equally impressive. The home's lower level is without air conditioning. There are incidental sources of heat due to the usage of the area as an office space, with numerous computers, printers, scanners, copiers, office lighting, etc. By employment of naturally venting the area at night by opening windows, moderate temperatures are maintained effectively during the hot summer days.

Without air conditioning, on a hot day in the upper 90°F or low- to mid-100°F, the lower level will maintain comfortable temperatures in the 70°F range. Figure 4.8

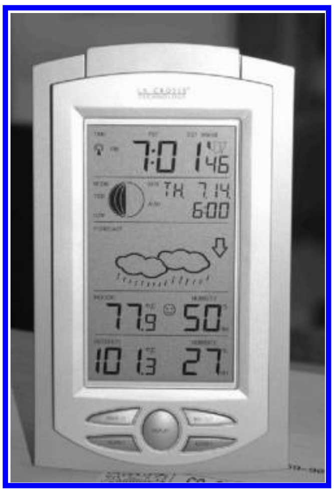

FIGURE 4.8 July 14, 2005. Summertime comfortable temperature spread of 23.4° maintained without mechanical cooling. (Author's photo.)

captured the temperature spread on July 17, 2005, at 7:01 p.m., when in a shaded area outside, the free air temperature was 101°F, while the interior maintained a maximum of 78°F—again, *without any air conditioning.*

4.8 ELEVATED CONCRETE FLOOR SYSTEMS

Elevated concrete floor systems have numerous advantages, which have historically been underutilized and undervalued in residential construction. The absence of the inclusion of concrete floors in residential applications has been due to multiple factors, including the relatively myopic view that residential structures by definition are to be constructed with wood-frame walls. The advantages of elevated concrete floors include the following:

- Fire is suppressed from floor to floor. Concrete floors easily resolve type II construction requirements.
- Acoustics are isolated. Noise transfer from floors above varies from being an annoyance to being a significant design issue. A few inches of concrete can resolve this.
- They are waterproof.
- They resolve structural issues of sheer transfer across the diaphragm.
- In high seismic zones, they can lower construction costs.
- In high wind threat zones, an elevated concrete floor increases the lateral resistance and will increase the durability of a multistory structure, particularly when combined with a concrete roof system.
- The concrete can be finished as the final floor finish as desired by stamping and/or staining, polishing, and sealing, thus eliminating the added cost of floor coverings or allowing architectural considerations that are otherwise not feasible.
- They can serve as a high thermal mass base material for radiant heat systems distributed by either hot water or hot air.

There are potential disadvantages to be considered:

- Concrete floors cannot readily be combined with wood-frame walls. Concrete or structural steel frame wall systems are required.
- Standard weight concrete cannot be supported by wood-frame floor joists.
- The cost of an elevated concrete floor has been viewed as being substantially less costly than conventional wood-frame/TJI joists, etc. (This is not universally the case, requires evaluation on a case-by-case basis, and is breaking down with the introduction of new alternatives for CIP floors.)
- Placing utilities in the floor system in a multistory structure can be somewhat more challenging than with frame construction and necessitates design considerations reflecting the nature of the floor.

4.8.1 CIP Floors

There are three primary methods for construction of CIP floors: B-Deck/PanDeck supported by bar joists/I-beams or such, a composite joist system such as Hambro™,

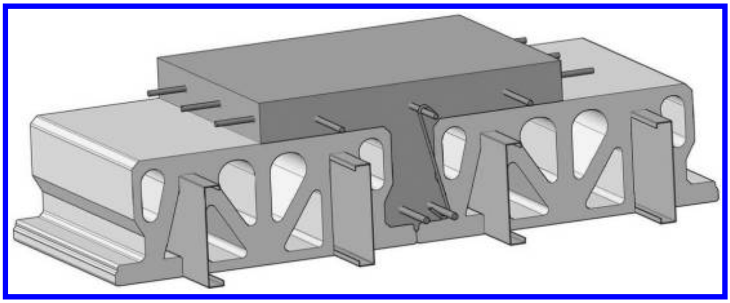

FIGURE 4.9 AmDeck ICF concrete floor system. (Courtesy of Amvic Building Systems.)

or an ICF-formed system where the concrete structure itself has ribbed drop beams that are the support.

ICF-formed system CIP floors have been gaining acceptance in residential and commercial applications due to their cost effectiveness and qualities including sound transfer suppression, inherent insulation, speed of construction, floor-to-floor safety factors (fire resistance), rigidity, sheer resistance, and durability. Figure 4.9, courtesy of Amvic Building Systems, illustrates a typical cross section of an ICF-formed floor or roof.

4.8.2 Precast Floor System

As discussed in this section, several systems have been developed to use thermal mass in precast structures (Figure 4.10). Air is circulated in the voids of hollow core floor and roof slabs. This system reduces the size of the required mechanical system and creates energy savings for heating in the winter as well as cooling in the summer. For heating, energy savings in the order of 35% can be achieved with this system. A reduction in cooling power consumption can be about 40%.

The underside of concrete floor and roof slabs should be exposed to get the full benefits of thermal mass. Doing away with a suspended ceiling can reduce the overall building height and can result in 5%–7% savings in construction costs. Using the thermal mass of concrete is extremely important from an environmental point of view because it provides a long-term economic gain for a building owner through reduced life-cycle costs.

When builders are facing height restrictions, employment of a precast floor may allow a design avenue to meet the restrictions of height due to the typically smaller section height of precast—typically, 6–8 in. versus 14–18 in. by other means. Also, precast floors can speed overall construction time when integrated together with CIP or ICF wall systems.

Precast concrete floors have a limitation in the lack of rigidity of the connection at the wall and as such are less effective in transverse sheer transfer and in high seismic zones may not be structurally satisfactory.

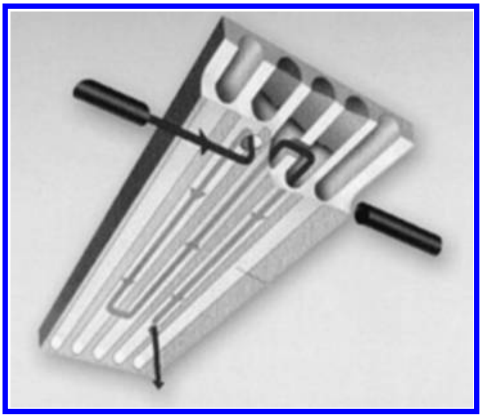

FIGURE 4.10 Typical insulated precast concrete floor system. (From http://www.sustainableprecast.ca/thermal_mass/precast_sustainability/canada/index.do.)

4.9 CONCRETE ROOF SYSTEMS

Concrete roof systems in single-family residential construction have historically been used primarily as a design element to counteract environmental issues. The two primary issues are strong winds (tropical storms, hurricanes, and typhoons) and biological attack or biodegradation. Historically, such concrete roofs were primarily constructed using removable conventional formwork and temporary shoring.

In residential construction today, two methods of constructing elevated floors with concrete have emerged as composite floors wherein a steel joist is partially embedded in the concrete deck, and EPS foam forms to fabricate the remaining concrete floor are used. A recent publication from the PCA gives an excellent summary of various available systems along with commercial organizations that provide more information on the topic.[2]

4.10 COMMERCIAL CASE STUDY

The Best Western Inn in Burlington, Ontario, Canada, was constructed with all external walls, corridor walls, and some of the interior partition walls of load-bearing concrete using a 6-in. concrete core ICF wall system. Elevated concrete floors are hollow core precast. The three-floor hotel has a total area of 33,900 $ft.^2$ (see Figures 4.11 and 4.12).

According to owner Amrat Patel, “This three-story hotel has 59 rooms, conference rooms, and an indoor pool. We have half the operating costs as the motel next door, which is half the size without a pool.” Mr. Patel goes on to say that, in addition to the greatly reduced operating costs, he has achieved a much faster return on investment, and the construction time was substantially reduced with less labor during the process.

The hotel is located near a very busy intersection of three major freeways, and exterior noise is an issue for the area. The guests consistently rate the hotel highly for providing a restful and quiet environment. Mr. Patel relates that he is realizing

FIGURE 4.11 Best Western, Burlington, Ontario, Canada. (Author's photo.)

FIGURE 4.12 Best Western during construction. (Courtesy of Amvic Building Systems.)

approximately a 20% annual savings in operating costs, when compared to another hotel of similar size that he also owns.

Drury Inns are located in multiple Midwestern and Southeastern locations. The St. Louis, Missouri, Drury Inns converted all six- and eight-story hotels to construction with an ICF exterior skin (see Figure 4.13). Their experience has been faster completion (averaging about 60 days per hotel compared to before they used ICF),

FIGURE 4.13 Drury Inn, Indianapolis, Indiana, under construction with ICF walls. (Courtesy of Amvic Building Systems.)

which generates approximately $1 million in increased revenue for each 30 days gained. Drury Inns has also noted increased job safety during construction, less job site damage to material, reduced operating costs, and less near- and long-term maintenance for their hotels.

There have been numerous structures built with a sustainable concrete system with insulation, as has been discussed in this chapter. They range from residential (case 1) to others in commercial types of constructions. The main purpose of these examples remains the same concerning energy saving, sustainability in terms of efficient use of materials, and excellent performance overall. The first case has been well published and is cited here as a personal experience of the author that has been well acclaimed.[3]

A house built in 1997 in Silver Spring, Maryland, just outside Washington, District of Columbia, used as little wood as possible (with a saving of over 60 trees as natural resources) and insulated concrete as one of the first few residential applications. In addition, all the interior walls were built with recycled, light-gage steel metal studs, which are quite common in commercial construction but not in residential. All floors were also concrete, with polypropylene fibers and the same concrete as in the external walls. In order to keep the construction light, a light-gage metal deck was used as formwork and remained with concrete and the steel beams to make an efficient concrete–steel composite floor system, which, although commonly used in bridges, is unique in residential construction. Finally, the staircases in this house were built with the leftover light-gage steel beams and studs to make even more impact on efficient use of the material.

The energy system was an innovative geothermal system using wells driven 200 ft. into the ground and using the natural phenomenon of approximately constant temperature of 58°F year round 3 ft. below the grade in that area. This house, shown

FIGURE 4.14 Energy-efficient home using insulated concrete. (From Sabnis, G. M. et al., *Green House: The Energy Efficient Home*, 2nd ed., Washington, DC, Drylongso Publications, 2008.)

in Figure 4.14, is a colonial style with a large, unobstructed basement without any center column and measures a footprint of 45 × 55 ft., resulting in a total under-roof area of 7000 ft.[2]. The energy bill has been very well managed due to the efficient use of natural and available resources.

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ADDITIONAL READING

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5 Concrete Pavements and Sustainability

*Thomas J. Van Dam and Peter Taylor**

CONTENTS

5.1 INTRODUCTION

Owners of the nation's roadway system are encouraging the use of sustainability best practices and in time may require them in their contracts. This is an important step toward a more sustainable infrastructure. But the following two features of the paving community handicap pavement owners, designers, material suppliers, and contractors:

- Straightforward information that clearly explains what sustainability means, how it is measured, and how it can be improved in the context of a roadway is limited.

* The material in this chapter is based on a previous publication by Van Dam and Taylor (2009) and is gratefully acknowledged.

- Street and road agencies must balance the increasing necessity to implement sustainable pavement best practices with many other critical challenges. Pavements are aging and deteriorating; traffic volumes and vehicle loads continue to increase, and roadway budgets are falling short of meeting these critical needs. These needs and costs must be balanced with the cost of improving pavement sustainability, which as yet is unquantifiable.

Many concrete-based solutions for new and existing pavements have elements that may improve the sustainability of a pavement system. Implementing sustainable pavement best practices helps owner agencies address their pavement performance and budget challenges because cost effectiveness and high performance are integral characteristics of sustainable solutions.

Sustainability in concrete pavements is simply good engineering, which always involves working with limited resources to achieve the best product possible. What has changed is the way the product is evaluated and the period of time over which it is evaluated. Whereas in the past, economic factors were paramount for evaluation, now sustainability requires that environmental and social factors be considered as well.

Further, the analysis must include the entire life cycle of the project, encompassing all impacts (both positive and negative) from the point of inception to the end of life, as shown in Figure 5.1. This type of system-wide analysis is often referred to as a "cradle-to-grave"—or, more appropriately, a "cradle-to-cradle"—analysis (McDonough and Braungart 2002). It is important to remember that sustainability is

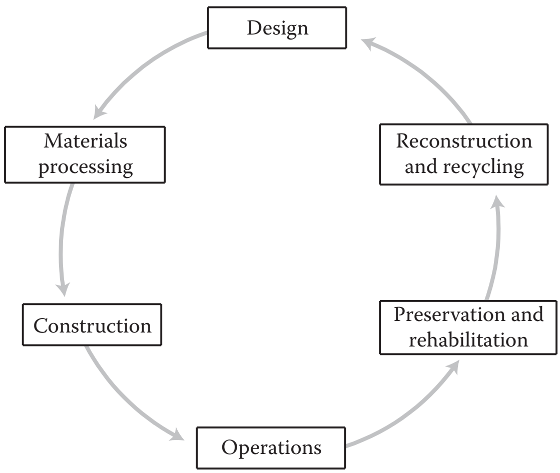

FIGURE 5.1 The concept of "good" pavement engineering must expand to cradle-to-cradle life-cycle performance. (From Van Dam, T. and P. C. Taylor, Building Sustainable Pavements with Concrete—Briefing Document, Ames, IA, CP Road Map, 2009. Available at http://www.cproadmap.org/publications/sustainability_briefing.pdf [accessed May 2011]. With permission.)

not about perfection. It is about balancing competing and often contradictory interests and making incremental improvements as our knowledge improves.

Finally, focusing on sustainability will make the concrete pavement industry more innovative and more competitive. This change can already be observed through the increasing emphasis on such diverse innovations as in-place recycling of existing concrete pavement, two-lift construction, safe and quiet surfaces, pervious concrete, optimized aggregate grading that facilitates reduced cementitious content, and concrete with higher percentages of supplementary cementitious material (SCM), to name a few. Each of these examples clearly demonstrates win–win–win scenarios having positive economic, environmental, and social impacts over the life cycle.

This chapter presents the details of many ways that we can make our pavements more sustainable using some basic principles outlined here with some examples.

5.2 COMMON-SENSE PRINCIPLES REGARDING SUSTAINABILITY

To approach concrete pavement sustainability in a practical fashion, it is necessary to link sustainability to familiar concepts in the pavement construction community. The following seven common-sense principles can help make this link:

- Principle 1: Get smart.
- Principle 2: Design to serve the community.
- Principle 3: Choose what you use.
- Principle 4: Less is more.
- Principle 5: Minimize negative impact.
- Principle 6: Take care of what you have.
- Principle 7: Innovate.

Each of these principles is discussed next, along with practical suggestions for employing the principles. It is important to consider each principle not only on its own merits but also in terms of its interdependency with and/or potential competition with other principles.

5.3 PRINCIPLE 1: GET SMART

This is an exhortation not to be content with the status quo. It is a call to educate yourself and your staff about making concrete pavements an integral part of sustainable infrastructure. Although it will require some formal training, education should not be restricted to traditional learning but rather should be integrated with day-to-day operations.

Much of this educational process needs to occur long before design and construction are initiated. Getting smart includes embracing the concept of the pavement life cycle. Various processes affect pavement sustainability during each stage of its life: design, material processing, construction, operations, preservation/rehabilitation, and reconstruction/recycling. The effects of these processes must be clearly understood so that processes can be appropriately applied. Clearly, this is a complicated and emerging science, but all of us can appreciate the interconnectivity of all life-cycle stages.

Specific actions that can be taken include the following:

- *Review relevant information.* A list of important documents and other materials is provided at the end of this chapter under "Additional Resources."
- *Learn how to design for what you need.* Excessive overdesign is wasteful, and underdesign results in unacceptable performance. Understand the principles and advantages of the mechanistic-empirical approach and the mechanistic approach to pavement design so that you can implement an appropriate approach for a given project.
- *Learn how to approach design holistically.* Understand the principles of incorporating pavement support conditions, material availability and properties, the environment and weather conditions, traffic, community considerations (see principle 2), etc., into sustainable pavement design and construction. In addition to determining slab thickness, other important design elements include material selection, joint spacing, load transfer, drainage, supporting layers, and surface texture (Smith and Hall 2001; Taylor et al. 2006).
- *Enhance educational programs.* Academic and developmental programs for new and practicing professionals need to be revised to address sustainability issues.
- *Use available tools and develop needed ones.* Learn about and implement current sustainable materials and practices. Encourage and support the development of needed materials and practices.

5.4 PRINCIPLE 2: DESIGN TO SERVE THE COMMUNITY

The second principle is obvious, yet it is often overlooked. It is often referred to as context-sensitive design (CSD), which entails meeting the needs of not only the user but also the impacted communities and the environment. The key to employing this principle successfully is recognizing that an approach meeting the needs of one application might not adequately meet the needs of another.

For example, a certain surface texture created to increase skid resistance to enhance safety has been demonstrated to have a significant impact on noise generation through tire–pavement interaction. The noise issue has been raised by communities adjacent to roadways; therefore, research was conducted to identify factors contributing to the objectionable noise (see Figure 5.2; Rasmussen et al. 2008). Mitigation strategies have been developed that have resulted in equally safe concrete riding surfaces that are also significantly quieter.

But the story does not end there. The same communities that object to noise generated on a high-speed roadway may have a different set of criteria for local, slow-speed roads serving their neighborhoods. In such locations, tire–pavement-generated noise may be far less an issue than aesthetics, high reflectivity, or surface drainage. It is even possible that an urban neighborhood might desire that "roughness" be designed into the surface to produce a calming effect to slow vehicles exceeding the speed limit and to create a more livable community.

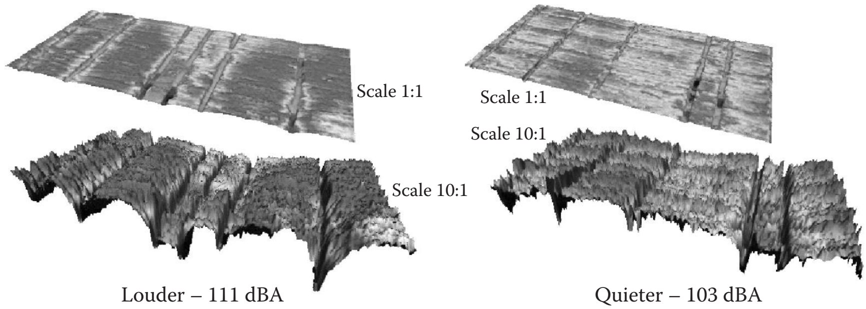

FIGURE 5.2 RoboTex scans of 100 × 200-mm samples showing variability of transverse tined surface and its effect on noise level. (Adapted from Rasmussen, R. O. et al., How to reduce tire-pavement noise: Interim best practices for constructing and texturing concrete pavement surfaces, TPF-5(139), Ames, IA, National Concrete Pavement Technology Center, 2008.)

It must be recognized, of course, that the needs of rural communities will differ from those of urban communities, as well as those of the "natural community," including the health of flora and fauna and the quality of air and water.

Successfully implementing this principle requires early involvement of everyone who is affected. Public involvement must be early and continuous. Although this will take time, it will ultimately result in increased societal acceptance and project efficiency by reducing expensive and time-consuming reworking of the project at a later date.

In the end, designing to serve the community will result in the construction of concrete pavements that reflect a sense of the place where they are built and that meld physically and visually within the surrounding environment and community. More detailed information on CSD can be found at http://www.contextsensitivesolutions.org.

5.5 PRINCIPLE 3: CHOOSE WHAT YOU USE

Often, little thought is given to the materials used in a concrete pavement other than whether they meet the specifications. The use of long-established specifications is appealing, but the automatic application of the same specifications year after year creates a barrier to the acceptance of rapidly evolving sustainable practices. A case in point is the use of recycled concrete, either as aggregate in new concrete or even as a base course underlying new pavement. Although concrete is the most recycled material in the United States—about 140 million tons/year (CMRA 2009)—many barriers still exist to using recycled material in concrete pavements.

For example, the single largest concrete recycling project ever undertaken was the complete recycling of Denver Stapleton Airport's pavements, which yielded 6.5 million tons of aggregate, much of which was used in concrete as aggregate (CMRA 2009). Yet, the Federal Aviation Administration (FAA) did not have a specification in place for the use of recycled concrete as a base material until an advisory circular (AC 150/5370-10C) was released in September 2007. And although many agencies, including the FAA, permit the use of coarse aggregate derived from recycled concrete, it is still uncommon in most locales. Specifications, test methods, acceptance criteria, and best-practice recommendations are needed to ensure that use of recycled concrete as aggregate is increased without compromising the quality of the final concrete pavement.

One premise of sustainable design is to use local materials to minimize transportation needs and the associated economic, environmental, and social impacts. Thus, the first element of this principle is to use the material closest to the project, which, of course, is the existing pavement structure. Whether it is concrete, hot-mix asphalt, or a combination of the two, the existing pavement surface and supporting layers can all be effectively used in the construction of new concrete pavement, with a significant positive impact on sustainability.

The Recycled Materials Resource Center (RMRC 2009) provides a good starting point to investigate various recycling options, and a list of additional references is found in the "Additional Resources" section at the end of this chapter. The shift in thinking that must occur is that the existing roadway is not something to be disposed of but instead is a source of valuable raw materials (e.g., a technical nutrient) for the reconstruction of the new pavement and an opportunity to eliminate waste (McDonough and Braungart 2002).

To the degree possible without sacrificing pavement quality, additional materials should be sought from local sources. This requires both knowledge of availability as well as an in-depth understanding of the engineering properties of the material being considered for use. It is not uncommon to find that a local material, such as coarse aggregate, has an undesirable property, such as poor wear resistance, susceptibility to freeze–thaw damage, or potential alkali–silica reactive (ASR) properties. A key to enhancing the sustainability of the concrete pavement is not to reject these materials out of hand but instead to understand the limitations inherent in the material and thoughtfully address them through proven technologies.

For example, an aggregate with poor wear resistance can still be used, just not alone at the surface; thus, two-lift concrete paving could be effectively used to address this limitation. Similarly, ASR-susceptible aggregates can be used if care is taken in selecting the cementitious material type and content. Replacement of Portland cement with certain industrial residuals, such as select fly ashes and slag cements, or even naturally derived pozzolans, such as volcanic ash, calcined clays, or rice husk ash, is extremely effective at mitigating ASR while reducing the environmental footprint of the concrete (more on this follows). Thus, being smart in selecting materials can significantly improve the overall sustainability of the project.

Finally, choosing what you use might mean transporting some materials at a great distance to overcome potential limitations in the locally available materials. In such cases, it is essential to minimize the amount of material transported to reduce the cost and the environmental and social impacts of transportation. Blending a freeze–thaw-durable, large-sized coarse aggregate with locally available intermediate-sized aggregate that has sufficient durability due its smaller size is one example of this approach. When possible, choose efficient modes of transportation, such as barge or rail, that are less environmentally damaging than transportation by truck.

5.6 PRINCIPLE 4: LESS IS MORE (BETTER)

Another common-sense principle of sustainable design is "less is more." Other factors being equal, a design that uses less virgin material is generally more sustainable as long as transportation mode and distance are similar. One element of this concept was discussed under principle 1: avoid wasteful overdesign. The focus of principle 4, however, is on reducing the use of Portland cement, the manufacture of which is expensive and energy-intensive and generates harmful emissions.

Modern cement plants are becoming increasingly efficient, often burning biomass and waste fuels to reduce CO_2 emissions. Still, it is unlikely that the amount of CO_2 produced per ton of clinker can be dramatically reduced. The proportion of clinker to cement, however, can be reduced. Under current ASTM C150 standards, companies manufacturing cement are now allowed to replace up to 5% of clinker with high-quality limestone, an additional 5% inorganic process additions (e.g., slag cement, fly ash), and up to 1% organic process additions (grinding aids). This allowance directly reduces clinker content of Portland cement. Another way to reduce CO_2 emissions related to cement manufacturing is simply to reduce the demand for Portland cement. Even small reductions of Portland cement content in concrete pavements will yield significant environmental savings. Multiple strategies can be employed to do this.

The first strategy is to replace some Portland cement in concrete mixtures with SCMs. These include certain reactive industrial by-products such as fly ashes, slag cement, and silica fume. SCMs also include certain naturally derived pozzolans like volcanic ashes and calcined clays (ASTM C618 Class N). Replacing 1% of Portland cement with SCM can result in an approximately 1% reduction in CO_2 production and energy consumption per unit of concrete. Using SCMs in concrete mixtures can also yield other benefits, including increased economy and enhanced concrete durability. Therefore, their appropriate use should always be considered.

Cement manufacturers offer various blended hydraulic cements (ASTM C595), which are composites of Portland cement and one or more SCMs (e.g., slag cement, pozzolan) or interground limestone. Typical Portland cement replacement levels for pavements can be as high as 50% for slag blends. Performance-specified hydraulic cements (ASTM C1157) are manufactured blended cements in which the composition of Portland cement and SCMs is not restricted. The kilograms of CO_2 generated per kilogram of blended hydraulic or performance-specified hydraulic cement can be reduced by as much as 30% or more compared to Portland cement.

In addition to manufactured blended cements, another way to incorporate SCMs in concrete mixtures is to add them to the mixture at the concrete plant. The concrete producer can choose to include SCMs such as fly ash, slag, natural pozzolans, and/or silica fume along with Portland cement, or with manufactured blended cement, as part of the batching process.

A second strategy for reducing the amount of Portland cement in concrete is to reduce the total cementitious material content. Traditionally, the mixtures used for concrete pavements have often had minimum cement content of 564 lb./yd.^{3} (six-sack mix). However, the use of optimized aggregate grading allows a significant reduction in cementitious material content, with some state departments of transportation using mixes with as little as 470 lb./yd.^{3} (Taylor et al. 2006).

Such mixes can have the additional benefit of being less prone to segregation and yet easily consolidated during slipform paving operations. Further, the resulting concrete is generally less prone to shrinkage and other negative effects resulting from high cement paste content.

5.7 PRINCIPLE 5: MINIMIZE NEGATIVE IMPACT

This principle encompasses ways to improve several construction and operational impacts that directly contribute to the sustainability of concrete pavement during the construction and operational phases of the life cycle. These impacts include the following:

- Noise from construction and traffic
- Safety: wet weather and nighttime driving
- Delays during new construction and during rehabilitation
- Pollution, particulates, and waste generated by construction and traffic
- Water use and treatment of runoff such as sawing slurry
- Energy efficiency: construction, traffic operations, and urban lighting
- Vehicle pavement interaction in which pavement characteristics such as roughness, texture, and deflection impact fuel efficiency
- Urban heat island effect or the observation that higher temperatures exist over built-up urban areas

It is impossible to cover all these impacts in detail here, but excellent sources of information are listed in the “Additional Resources” section at the end of this chapter. In general, construction that enhances sustainability will seek to minimize noise levels; provide a safe environment for workers; minimize disruption of service to the traveling public and community; produce fewer emissions, particulates, and construction waste products; reduce water use; and increase efficiency of equipment and processes.

Once constructed, the concrete pavement should provide a quiet and safe surface under vehicle operations, require minimal preservation and rehabilitation through its life, effectively address water runoff, improve the energy efficiency of vehicles operating on it through reduced rolling resistance (related to roughness, texture, and deflection), reduce the energy required for artificial lighting, and mitigate the heat island effect through the pavement’s reflectivity.

Recently completed research has determined ways that concrete pavements can be constructed or restored to be extremely quiet and safe through the use of drag-textured or longitudinally tined surfaces or through diamond grinding (Rasmussen et al. 2007). There have also been tremendous advances in minimizing water use during construction through the reuse of wash water and through treating runoff from pervious surfaces (NRMCA 2009).

Interest in mitigating the urban heat island effect continues to increase with the use of reflective paving materials, including conventional concrete, being recommended as a mitigation strategy (EPA 2009). Additives that can further increase the reflectivity (albedo) of concrete, such as slag cement or light-colored fly ash, are also recommended.

5.8 PRINCIPLE 6: TAKE CARE OF WHAT YOU HAVE

This principle emphasizes the need to take care of existing pavements. Like any product, with time and use, concrete pavements eventually deteriorate. Just as vehicles that are well maintained keep their value longer and can provide more miles of service, pavements that are well maintained deteriorate more slowly and have longer service lives. A proactive approach to sustainable pavements through preservation and rehabilitation requires agencies to

- Focus more time and effort on upfront evaluation of existing pavement conditions
- Stay informed about new or improved preservation and rehabilitation technologies and practices
- Systematically deploy optimum preventive maintenance activities, preserving pavements in good condition and extending their high level of service
- Systematically deploy optimum preservation and rehabilitation technologies and solutions resulting in smoother, more durable pavements with improved surface friction characteristics

One of the most important, but easily ignored, elements of such an approach is preventive maintenance. Preventive maintenance activities are accomplished when a pavement is still in good condition. With minimal investment, these activities restore or enhance and extend a pavement's original level of service. The window for preventive maintenance is approximately 10–15 years. Conducting timely, appropriate preventive maintenance on a routine basis can extend a pavement's life significantly. The most common preventive maintenance treatments are partial-depth repairs, full-depth repairs, dowel bar retrofit, joint resealing and crack sealing, and diamond grinding.

Diamond grinding is typically used to restore ride quality after repairs are completed. This technique also improves skid resistance, significantly reduces tire–pavement noise, and can be applied two or three times over the life of the pavement (Correa and Wong 2001). The technique was first used on a section of I-10 in California in 1965, and the same section was subsequently ground in 1983 and again in 1997. This section is still in service today, carrying 2.25 million equivalent single-axle loads.

One rehabilitation strategy is the use of bonded or unbonded concrete overlays (see Figure 5.3). Unbonded overlays in particular are high-performing rehabilitation strategies for concrete, asphalt, and composite pavements (Harrington and Fick 2014). By taking advantage of the existing pavement's remaining structural capacity, an overlay requires only a minimum of new material to restore or even enhance the pavement's structural and functional performance.

If appropriate and timely maintenance is not carried out, a pavement's condition will continue to deteriorate. Studies have shown that once a pavement's condition has deteriorated to the point that only 40% of its life remains, the rate of deterioration accelerates. Then, pavement condition can drop by as much as 60% in only 12% of design life. Once a pavement's condition is beyond the preventive maintenance window, the pavement has entered the rehabilitation phase and requires structural restoration.

FIGURE 5.3 Concrete overlays can restore or enhance an existing pavement's functional and structural performance. (From Van Dam, T. and P. C. Taylor, Building Sustainable Pavements with Concrete—Briefing Document, Ames, IA, CP Road Map, 2009. Available at http://www.cproadmap.org/publications/sustainability_briefing.pdf [accessed May 2011]. With permission.)

As with any other structure, there comes a time when a concrete pavement has reached the end of its service life. However, the concrete can still be recycled into the base of a new pavement, in place or elsewhere, or as an aggregate for new concrete. In recent years, dramatic improvements have been made in recycling of concrete pavements.

As discussed previously, a proactive, life-cycle approach to pavement preservation and rehabilitation is required. Fortunately, highway agencies have access to information about a variety of effective concrete-based maintenance and other preservation and rehabilitation strategies to preserve the equity in existing pavements and enhance their functional and structural capacity for less than the cost of reconstruction. Many such strategies, some mentioned briefly earlier, are described in *The Concrete Pavement Preservation Workshop Reference Manual* (Smith et al. 2008).

5.9 PRINCIPLE 7: INNOVATE

Adopting a sustainable approach to pavements requires agencies and industry to develop new ways of thinking and doing. We can no longer base decisions on economic impacts alone, especially first costs. We must consider environmental and social impacts as well, spanning the entire pavement life cycle. Developing win–win–win solutions challenges our abilities to create and innovate.

An important innovation under development is high-SCM content cementitious binder systems. Variations of such systems were used in elements of the I-35W bridge reconstruction project in Minneapolis (see Table 5.1; ACI 2009). The concrete piers contained only 15% Portland cement (with 18% fly ash and 67% slag cement). This system resulted not only in economic savings but also in enhanced constructability. The heat of hydration was significantly reduced, and thus thermal stresses in the large piers were mitigated during construction. This system also had significant environmental benefits because it reduced the carbon footprint and embodied energy of the concrete mixture by approximately 75%. This bridge was aesthetically enhanced with gateway sculptures (30 ft. [9 m] tall) made of concrete containing innovative new cement that removes carbon monoxide, nitrogen oxides, and sulfur dioxide from the atmosphere by photocatalytic reaction.

Social benefits of the mixtures used in the I-35W bridge project are more difficult to quantify. They include a reduced amount of waste material (fly ash and slag) going to landfill and a lighter-colored concrete, which reduces the urban heat island effect.

Another emerging technology related to cement is reduced CO_2 binders (e.g., magnesium silicates, geopolymers) and potential binders that sequester CO_2 during their production. Although these binders are currently under development, it is easy to imagine that in the not too distant future, concrete pavements will be constructed from low to no CO_2 cement-based binders.

Aggregates manufactured from CO_2 and seawater may someday be available. Such aggregates could make concrete of the future a CO_2 sink instead of a source (Constantz and Holland 2009). Many other innovations are already beginning to impact the concrete paving industry positively, including overlays, two-lift construction, next-generation diamond grinding, internal curing, and precast pavement elements, to name a few. Life cycle-based approaches encourage innovations such as these.

The key to enacting this principle is creating partnerships among various concrete pavement funding agencies, designers, material suppliers, contractors, and other interested organizations and community representatives. Essential to such partnerships is shared risk. Adopting innovative approaches is always more challenging than doing what is familiar. If unexpected results occur, it is important to determine

TABLE 5.1
Concrete Mixtures Used on the Reconstructed I-35W Bridge

			Cementitious Materials				
Component	**Specified Strength (psi)**	**w/cm**	**Total (lb./yd.^{3})**	**Portland Cement (%)**	**Fly Ash (%)**	**Slag (%)**	**Silica Fume (%)**
Superstructure	6500	0.35	700	71	25	–	4
Piers	4000	0.45	575	15	18	67	–
Footings	5000–5500	0.45	<600	40	18	42	–
Drilled shafts	5000	0.38	<600	40	18	42	–

Source: ACI, *Concrete International*, 31 (2), 2009.

what went wrong, correct it for the next iteration, and, ultimately, adopt those technologies that prove to be promising.

5.10 MEASUREMENT OF SUSTAINABILITY

Ideally, an eighth principle would be "measure." The best way to determine a pavement solution's sustainability would be to employ a methodology that measures and compares economic, environmental, and societal factors influenced by the pavement over its entire life cycle (Figure 5.4). The methodology could be used in several ways:

- To benchmark current practice and assess improvements as they are implemented
- To compare different systems or solutions on an equitable basis
- To assess the relative benefits of alternative approaches to design, material selection, etc.

However, such a comprehensive evaluation methodology is not yet ready to be implemented. Although economic factors have been identified and can be measured reasonably well through life-cycle cost analysis (LCCA), a suite of appropriate environmental and social factors has not yet been identified or generally accepted by the industry, and corresponding measurement tools are not generally available, although rating systems provide a way to quantify some of these factors. The topic of measuring sustainability is extremely complex, and considerable debate regarding the details is ongoing.

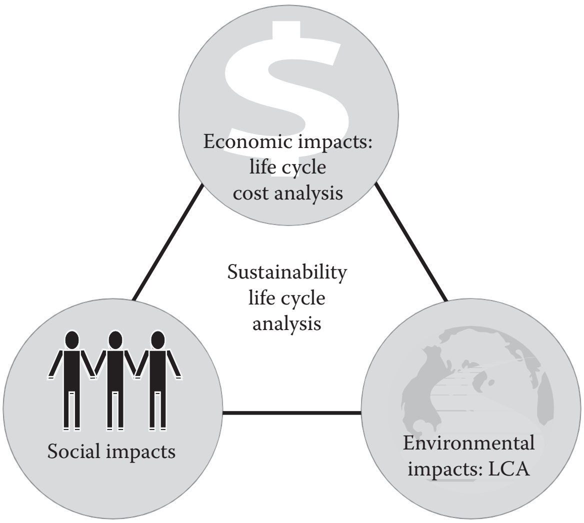

FIGURE 5.4 Economic, environmental, and social factors must be identified, measured, and balanced. (From Van Dam, T. and P. C. Taylor, Building Sustainable Pavements with Concrete—Briefing Document, Ames, IA, CP Road Map, 2009. Available at http://www.cproadmap.org/publications/sustainability_briefing.pdf [accessed May 2011]. With permission.)

5.10.1 Economic Factors Related to Sustainability

Good engineering practice for any project or system balances the need to minimize economic costs with the need to maximize efficiency, quality, and longevity. However, if attempts to minimize economic costs focus primarily on first (or initial) costs, engineers miss the opportunity to make informed decisions that affect future generations and long-term pavement sustainability. Therefore, economic costs should be analyzed across a system's entire life cycle using an LCCA method, such as the Real Cost program (FHWA 2009).

An LCCA is based on sound economic principles. In terms of dollars, the method considers the time value of money, initial and anticipated future costs, and ultimate value at the end of service life. Most LCCA approaches used by agencies include only agency costs, such as the costs of initial construction, preservation, and rehabilitation, as well as salvage value. It is possible and maybe even desirable to include user costs in the LCCA. Such costs include, for example, financial costs to the traveling public caused by road preservation and maintenance activities. If included, user costs can quickly overwhelm agency costs. Still, this type of LCCA can provide a framework for considering trade-offs between user costs and agency costs.

Other economic costs that can be considered include the financial cost of environmental cleanup if a significant environmental impact is anticipated. Additionally, if a carbon cap-and-trade system is adopted, analyzing the economic impacts may provide one means of assessing, through an LCCA, the environmental impacts of the production of carbon dioxide.

5.10.2 Environmental Factors Related to Sustainability

Currently, environmental factors contributing to the sustainability of concrete pavements can be assessed in one of two ways. The first is to use one of the emerging rating systems based loosely on the Leadership in Energy and Environmental Design (LEED) green building rating system (USGBC 2008). For concrete pavements, a few examples of such systems include the following:

- Greenroads® (https://www.greenroads.org/): a rating system that includes pavements developed at the University of Washington with industry participation (Muench et al. 2011)
- INVEST (https://www.sustainablehighways.org/): a self-evaluation rating system developed for the FHWA
- GreenLITES: a certification program instituted by the state of New York (NYSDOT 2008)

Whereas LEED has evolved over the last decade into a widely accepted approach for rating the environmental impact of buildings, systems for rating the environmental impact of pavements are still in the development stages and have yet to be broadly adopted. Further, by their very nature, rating systems simplify complex issues and may deliver an inappropriate assessment of some innovative pavement solutions. Thus, care must be exercised when using such systems because inappropriate measures and weightings may be applied to establish the rating. In time, as these systems evolve and improve, they likely will provide a simple approach to assess quickly the environmental factors related to concrete pavement sustainability.

In contrast to the rating systems and their inherent simplifications, the second method for assessing environmental factors—a detailed life-cycle assessment (LCA)—offers a more complex approach. The primary example is the International Organization of Standardization's (ISO's) guideline ISO 14040:2006, *Environmental management—Life-cycle assessment—Principles and framework* (ISO 2009). This guideline describes how to conduct an LCA that accounts for all the individual environmental flows to and from a concrete pavement throughout its entire life cycle, from material extraction and processing to construction, operations, restoration, and rehabilitation, and, ultimately, to the end of service life and disposal/recycling.

Although the ISO guideline describes the LCA principles and framework, it does not describe the LCA technique in detail or specify methodologies for individual phases of the LCA. Instead, several companies employ methodologies that adhere to ISO 14040:2006 guidelines. Work conducted for the Portland Cement Association to develop a life-cycle inventory (LCI) for Portland cement concrete followed ISO 14040 guidelines (Marceau et al. 2007).

Based on these efforts and others, the following environmentally based parameters can be recommended for assessing the environmental impact of pavements in general and concrete pavements specifically

- Embodied energy
- Emissions/global warming potential
- Toxicity potential
- Raw material consumption
- Waste generated

5.11 CASE STUDY: TWO-LIFT CONCRETE PAVEMENT CONSTRUCTION

The Missouri Department of Transportation (MODOT) constructed (2010–2011) an innovative concrete pavement on Route 141 in St. Louis featuring the use of two-lift construction. This technique is not new; it was the standard practice for the construction of the first concrete pavements in the United States. These early pavements, known as R. S. Blome granitoid pavements, consisted of a 5- to 6-in. (12.5- to 15-cm)-thick lower lift of tamped concrete containing large, angular, and coarse aggregate topped with a 1.5- to 2-in. (4- to 5-cm) surface lift made of carefully screened fine aggregate chips. The two lifts were placed "wet on wet," creating a monolithic structure. The surface was carefully finished in a brick-like pattern to provide a nonslip surface for horses. Many of these pavements, which are now over 100 years old, remain in service in communities throughout the United States.

More recently, two-lift concrete pavements using a "wet-on-wet" approach have been constructed for decades in a number of European countries, including Austria and Germany. These pavements are built almost exclusively for heavy-duty motorways and have been designed for 30 years or more of maintenance-free service life.

In Europe, it is common to use recycled concrete aggregate in the bottom lift and, in some cases, even intermixed with recycled asphalt pavement, a practice being utilized today in the United States in concrete pavements being constructed by the Illinois Tollway. The bottom lift is placed using very stiff concrete and is typically paved 8.25 in. (21 cm) thick. This is then immediately topped with a 1.6-in. (4-cm)-thick surface lift made with carefully graded smaller (5/16 in. [8 mm]) aggregates. European practice often exposes the aggregates through the application of a retarder and surface brushing, creating the desired skid resistance and noise reduction.

The first large-scale demonstration of this technology in the United States took place in Detroit, Michigan, on I-94 in 1994. But it was not until 2008, with the construction of a two-lift concrete pavement on I-70 near Salina, Kansas, and the conducting of the 2008 National Two-Lift Open House (see http://www.cptechcenter.org/projects/two-lift-paving/index.cfm), that the sustainability attributes of this technique began to be realized in the United States. As a result of this successful demonstration in Kansas, MODOT decided to demonstrate the technology in an urban environment, further improving the sustainability attributes of the surface through the use of a photocatalytic (titanium dioxide) containing cement. The use of this cement in the surface lift actively removes nitrous oxide gases from the atmosphere, makes the surface highly reflective, and keeps it clean, thus lowering the urban heat island effect. It is believed that this latter effect will lead to significant reductions in carbon dioxide through compensation of the global heating effect. This same project features the use of pervious concrete shoulders, which allow surface runoff to pass through the pavement directly into the ground, naturally treating contaminants, recharging the groundwater, and mitigating storm runoff into surface waters. The project features three different test sections:

1. Control section placed conventionally as a single lift; conventional asphalt and concrete shoulders included
2. Two-lift concrete pavement section, with the top 2-in. (5-cm) lift containing photocatalytic cement to help abate nitrous oxides and carbon dioxide; conventional concrete shoulders included
3. Two-lift concrete pavement section, with top 2-in. lift containing photocatalytic cement to help abate nitrous oxides and carbon dioxide; pervious concrete shoulders included

Figure 5.5 illustrates the two concrete pavement sections, and Table 5.2 shows the conventional concrete mixture and the two concrete mixtures used for the top and bottom lifts. As can be seen, both concrete mixtures in the two lifts contain fly ash and reduced cementitious materials content. A comparative environmental impact analysis was conducted, evaluating the carbon footprint of the two concrete surfaces. The analysis considered cradle-to-placement materials, transportation, and concrete plant operations, with one lane mile of pavement selected as the functional unit.

Figure 5.6 presents comparative plots of the carbon footprint of the conventional concrete pavement versus the two-lift concrete pavement. It is seen that although the carbon dioxide produced due to batching and transportation is similar, due to materials, it is significantly higher for the conventional concrete pavement. Since

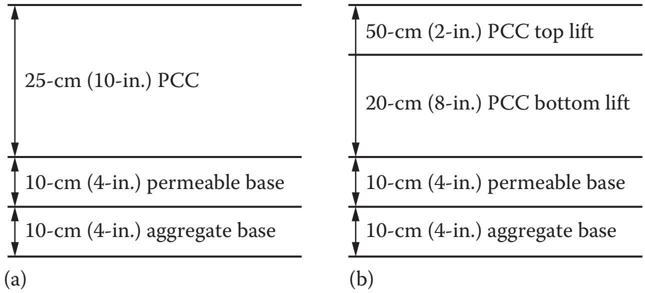

FIGURE 5.5 Conventional MODOT design (a) compared to two-lift design (b).

TABLE 5.2
Concrete Mixture Designs Used on MODOT Two-Lift Project

Material	Conventional kg/m³ (lb./yd.³)	Top Lift kg/m³ (lb./yd.³)	Bottom Lift kg/m³ (lb./yd.³)
Cement	332 (560)	240 (405)	204 (344)
Fly ash	0 (0)	80 (135)	68 (115)
Water	133 (224)	128 (216)	109 (184)
Fine aggregate	698 (1177)	739 (1246)	834 (1406)
Coarse aggregate	1143 (1927)	1114 (1877)	1110 (1871)

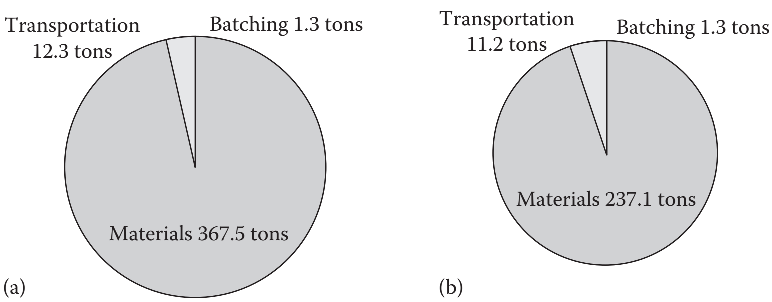

FIGURE 5.6 Carbon footprint, in tons of carbon dioxide per lane mile of conventional (a) vs. two-lift (b) pavement sections. (For more information, contact Brett Trautman of the Missouri DOT [brett.trautman@modot.mo.gov] or Tom Cackler of the National Concrete Pavement Technology Center [tcackler@iastate.edu]).

the materials are responsible for approximately 95% of the carbon dioxide associated with the construction of the concrete surface, the overall carbon footprint of the conventional pavement (381 tons of carbon dioxide per lane mile) is significantly higher than for the two-lift pavement (250 tons of carbon dioxide per lane mile). This project illustrates how design and materials can be optimized to reduce the carbon footprint of a concrete pavement significantly.

5.12 SOCIETAL FACTORS RELATED TO SUSTAINABILITY

Societies, particularly the United States, are utterly dependent on the ability of people and goods to move rapidly and efficiently from place to place. The mobility that pavements provide is one critical social factor in their overall sustainability. Another social factor is the effect of pavements on the quality of life in surrounding communities (by virtue of their appearance, location, contribution to traffic noise, impacts on safety, etc.).

Although the pavement industry has made progress in developing tools for analyzing two sustainability factors—LCCAs for analyzing economic factors and rating systems and early LCAs for measuring environmental factors—no system is yet available for assessing social factors. The following are several potential parameters that would need to be included in such an assessment:

- Safety
- User delays
- Noise
- Energy

5.13 WHERE DO WE GO FROM HERE?

As discussed previously, concrete pavement stakeholders already have a toolbox of best practices that can have a positive impact on pavement sustainability. In addition, progress is being made on developing life-cycle systems that will analyze economic, environmental, and social factors related to pavement sustainability. Identified research needs include

- Development of advanced materials and processes that optimize reuse and conservation and that measurably reduce waste, energy consumption, water usage, and pollutants generated during all phases of the pavement's life cycle
- Creation of innovative designs that make full use of the versatility of concrete as a paving material to improve pavement sustainability
- Adoption of construction practices that directly enhance the overall sustainability of concrete pavements through increased efficiency, reduced emissions and waste, and decreased social disruption
- Application of preservation, rehabilitation, and recycling strategies to newly constructed concrete pavements that enhance the sustainability of the existing network of concrete pavements
- Refinement of life-cycle cost analyses to account fully for the economic attributes of sustainable concrete pavements
- Acquisition, preservation, and distribution of data as part of an environmental LCI that accounts for all the individual environmental flows to and from a concrete pavement throughout its entire life cycle and the adoption of an internationally recognized environmental life-cycle analysis approach that examines the environmental aspects of concrete pavements through their life cycles

- Identification and quantification of social considerations that are affected by concrete pavement and inclusion of these considerations in the integrated design process
- Development of strategy selection criteria to assist in the decision-making process and to allow various alternatives to be compared based on economic, environmental, and social considerations
- Distribution of technology transfer for existing concrete pavement technologies that support the "triple bottom line" of economic, environmental, and societal sustainability

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ADDITIONAL RESOURCES

Centers, Associations, and Societies

American Concrete Institute Committee 130 Sustainability: http://www.concrete.org/COMMITTEES/committeehome.asp?committee_code=0000130-00
American Concrete Pavement Association: http://www.acpa.org/
American Society of Civil Engineers: http://www.asce.org/professional/sustainability/
Cement Association of Canada: http://www.cement.ca/
Context Sensitive Solutions: http://www.contextsensitivesolutions.org/
CP Tech Center: http://www.cptechcenter.org
Green Highways Partnership: http://www.greenhighways.org/
International Grooving and Grinding Association: http://www.igga.net/
Materials in Sustainable Transportation Infrastructure: http://www.misti.mtu. edu/index.php
Portland Cement Association: http://www.cement.org/SD/index.asp
Recycled Materials Resource Center: http://www.recycledmaterials.org/
National Ready Mix Concrete Association: http://www.nrmca.org/sustainability/index.asp

Producers

BASF: http://www.basf.com/group/corporate/en/content/sustainability/eco-efficiency-analysis/index
LCA Tools
Leadership in Energy and Environmental Design: http://www.usgbc.org/Default.aspx

Federal Agencies

Environmental Protection Agency: http://www.epa.gov/
Greenroads: http://pavementinteractive.org/index.php?title=Green_roads
FHWA: http://www.fhwa.dot.gov/pavement/concrete/
FHWA Context Sensitive Design: http://www.fhwa.dot.gov/context/index.cfm
Green Streets Calculator: http://1734298.sites.myregisteredsite.com/green11/calculator.aspx
Measure of Sustainability: http://www.canadianarchitect.com/asf/perspectives_sustainibility/measures_of_sustainablity/measures_of_sustainablity_intro.htm
National Renewable Energy Laboratory: http://www.nrel.gov/lci/
Real Cost: http://www.fhwa.dot.gov/infrastructure/asstmgmt/rc21toc.cfm

6 Roller-Compacted Concrete

A Sustainable Alternative

Chetan Hazaree, Ponnosamy Ramasamy, and David W. Pittman

CONTENTS

6.1 INTRODUCTION

The awareness regarding sustainable development is increasing. Propagated mainly by the experiences of the developed countries, sustainability is now getting applied to almost all levels of human development, viz., infrastructure, systems, and communities; the rate of such applications is rather slow. What are gradually getting imbibed are the "sustainability sense" and consequently the aspiration to evolve systems for measuring sustainability in a consolidated way while being cognizant of the social–economical–environmental and their interactional influences.

Roller-compacted concrete (RCC) is a relatively new development in civil and construction engineering and has been used in the last 45 years in specific applications in large water-retaining structures and pavement infrastructure systems. The term RCC refers to both a construction material and a construction technique, with inherent time–cost–resource benefits, making it a holistic and sustainable construction system. With infrastructure systems playing decisive roles in influencing the economies, stability, and development of any nation, it is imperative to appreciate and critically evaluate the existing ways of using depleting natural or relevant man-made resources from a sustainability perspective. Additionally, there is a need to find sustainable practices for such construction, repair, and rehabilitation. RCC offers one such alternative. This chapter aims at providing a synoptic understanding of RCC as a material and construction method as used for surface transport and hydraulic structures.

6.1.1 Definitions

RCC is defined both as a concrete material and a construction technology. For the sake of clarity, the following definitions and abbreviations will be used in this chapter. RCC as a material is defined as a concrete compacted by roller compaction; it is concrete that in its unhardened state will support a roller (often vibratory) while being compacted. Roller compaction is a process of compacting concrete using a vibratory roller [1,2]. While RCC technology (RCCT) is a technology characterized mainly by the use of rollers for compaction, it is neither a design criterion nor a design technology [2]. The concrete mostly used for such construction is relatively dry, has zero slump, and is capable of supporting and being compacted using external (vibratory) compacting equipment.

Depending primarily on the application, RCC was/is also known by the following names: rollcrete; rolled concrete; no-slump concrete; dry lean concrete; cement-treated base (CTB); and econocrete. The common features of any of these applications are the types and composition of the constituents and the basic elements of the construction techniques. There may also be specific differences that make each named technique unique. In this chapter, RCCP refers to RCC pavements and RCCD refers to RCC dams.

6.1.2 Deviation from Conventional Relation

Abrams' law of water/cement ratio and strength is valid only for fully compacted concrete; it tends to deviate when water is reduced below a certain limit. Figure 6.1 shows a general relationship between strength and water/cementitious materials ratio (w/cm) [3]. For concretes that can be fully compacted, the strength, instead of increasing, reduces as the w/cm increases. Below a certain threshold, depending on the constituent materials and mixing technique, the strength drops down and follows a curve resembling the moisture–density relationship (Proctor curve) in soils. See Figure 6.2 [4].

The philosophy of RCC mixture design operates at that optimal point where the strength starts to deviate from following Abrams' law. RCC has to be fully compactable, however, at much lower water content than conventional concrete. Any further decrease in water could leave RCC with higher voids, resulting in lowering of strength and other durability indices. An RCC mixture has to be just wet enough to be fully compactable yet stiff enough to support a roller; it is quite a balancing act to perform.

The consistency of RCC is measured using a Vebe consistometer. This rugged apparatus (see Figure 6.3) can be used in the lab and field and gives a relative time estimate for the paste to rise to the top under vibration with a sustained surcharge loading on top of the concrete [3]. This test method is meant to emulate the

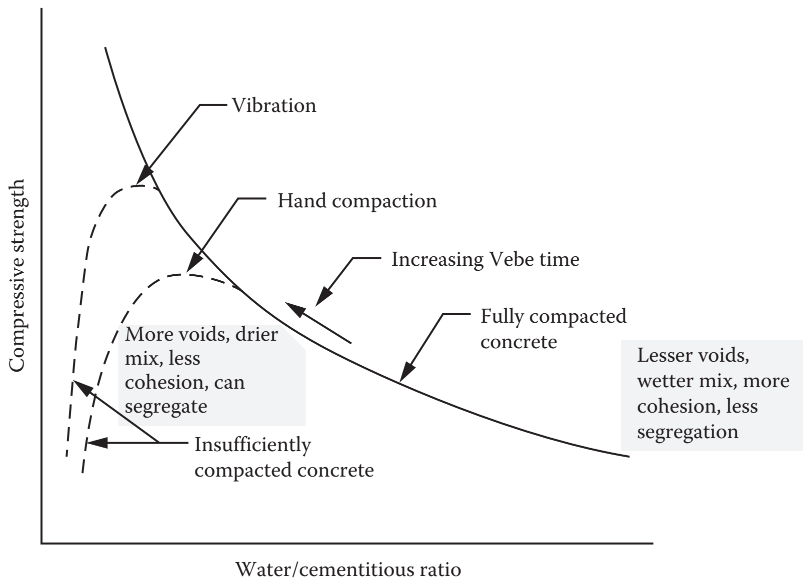

FIGURE 6.1 General relationship between compressive strength and w/cm ratio. (From ACI Committee 207, *Report on Roller-Compacted Mass Concrete*, Farmington Hills, MI, ACI, 2011.)

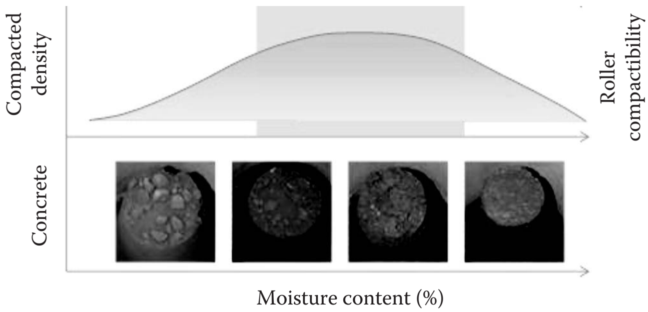

FIGURE 6.2 Typical moisture–density profile and appearance of concrete mixtures. (From Hazaree, C V, *Workability and Strength Attributes of RCC: Effects of Different Chemical Admixtures and Resulting Paste*, Ames, IA, Iowa State University, 2010.)

FIGURE 6.3 Vebe consistometer. (From ACI Committee 207, *Report on Roller-Compacted Mass Concrete*, Farmington Hills, MI, ACI, 2011.)

consolidating effects of the roller compaction in the field. The surcharge loading varies with the design philosophy and application of RCC.

6.1.3 Background

RCC originated almost 105 years ago; the earliest form of RCC pavement was built in Grand Forks, ND, in 1910, followed by pavements in Sweden in 1930s and in Belgium in 1935 [2]. The US Army Corps of Engineers (USACE) built an RCC runway in Yakima, Washington, in 1942 [5]. By the 1960s, CTB was used in the Oregon logging industry. In Vancouver, it was used for a log-sorting yard in 1976. The CTB was improved in this case by increasing the cement content of the soil–cement mixture from 6% to 12% by weight. This cement base gave good performance even without an asphalt overlay, which led to further development of RCC. This improved CTB was stronger and more resistant to freeze–thaw (F–T) damage, could resist petroleum spillage attacks, allowed faster vehicle speeds, and required less maintenance than gravel surfaces. The USACE started to investigate using RCC pavements in the 1980s and has since become a strong advocate for RCC pavements [6]. Figure 6.4 presents a pictorial view of the developments in RCC technology for pavement applications [7].

Applications of RCCP subsequently grew, although at a much slower pace. In the last couple of decades, the applications have increased dramatically, especially in the United States. Although the military use of RCCP in the United States began to decline in the 1990s, public and especially private/industrial RCCP applications have experienced a dramatic increase. Typical applications include industry facilities, where heavy load-carrying capacity and rapid wear and tear are anticipated, such as areas covered by off-road weigh stations; pavement bases in composite pavements; airport aprons, docks, and container ports; multimodal facilities and parking facilities, log sorting yards and waste-handling facilities, highway shoulders, and hardstands for military tanks and equipment. RCCP has also been used as a base layer in composite pavements.

The application of RCCD started more as a need rather than a systematic discovery. In this chapter, the term hydraulic structures and dams have been used interchangeably. While the need for rapid construction and increase in the hydraulic infrastructure was pushing on one hand, there was also a need to make such construction more viable, repair-free, and economical, on the other. Traditional methods of concrete dam construction are relatively slower and discontinuous (discrete), whereas improvements taking place in the earth-moving equipment in the early 1970s were making construction of earth and rock-filled dams faster and therefore more cost effective. In a pursuit of answering these questions, and to evolve an economical and optimum gravity dam, the concept of RCCD was first postulated and proposed in theory and in practice in 1970 by Raphael [8] in his paper, *The Optimum Gravity Dam*, and was strengthened further for potential savings in 1972 [9]. This proposal combined the concept of concrete strength and soil compaction to render a stronger, faster, and economical solution for dam construction.

The first major project to use large volumes of RCC (rollcrete) worldwide was for rehabilitation works at 143-m-high Tarbela Dam in Pakistan, which started in 1974 [10]. In the 1970s and early 1980s, some work was going on at the USACE (on rollcrete), in the United Kingdom (high-paste RCC), and in Japan (on roller-compacted dam [RCD]) [3]. As confidence was established in the cost-, time-, and resource-saving potential of RCC, more countries across the globe started adopting RCC. Today, more than 450 RCC dams are standing (some are under construction) worldwide, and many more applications are planned.

As the applications of RCC increased, the need for adapting to local conditions and overcoming challenges also grew with experience. Successes and failures are changing the way RCC was originally done. Successful innovations such as development of sloped layer method (SLM), grout-enriched RCC (GERCC), use of slipform paving over GERCC, rock trenching of galleries, and use of precast for spillway ogee crests [11] are continuously being applied, making RCC ever fresh and interesting as a civil engineering system.

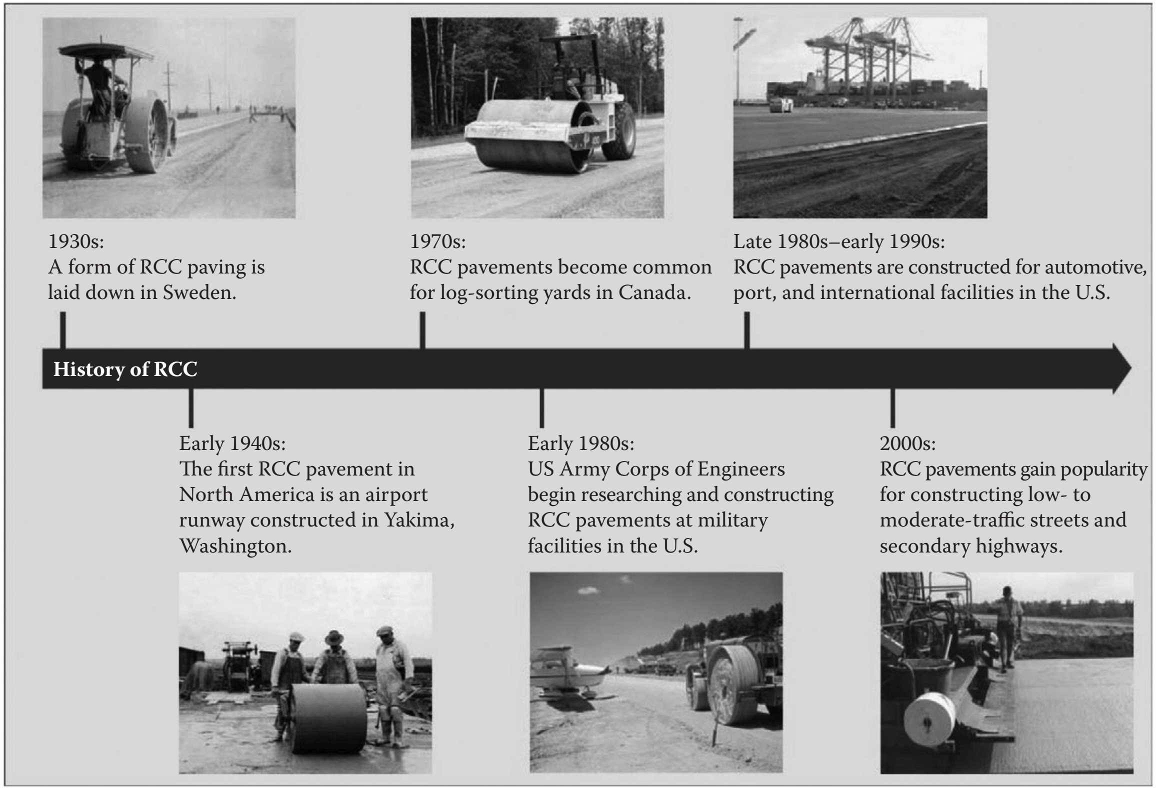

FIGURE 6.4 Glimpse of the historical evolution of RCC for pavements. (From Harrington, D et al., *Guide for Roller Compacted Concrete Pavements*, Ames, IA, CP Tech Center and PCA, 2010.)

6.2 RELATIVE ASSESSMENT

As a concrete material, RCC has no slump, is stiff, has lower water content, handles more like soil, and then sets up to become true concrete, exhibiting concrete properties. A freshly compacted RCC can actually be perceived as consisting of an aggregate skeleton coated with a thin layer of relatively drier cement paste [12]. The following sections sample out significant differences of RCC with conventionally vibrated concrete (CVC).

6.2.1 With Conventional Concrete

Table 6.1 presents a synoptic comparison between CVC and RCC.

It is relevant to note that the conditionings of aggregates for CVC as well as RCC are almost similar. Shrinkage is a dominant criterion for thermal properties in massive dam structures. Alkali aggregate reactivity is expansive if not treated. Abrasion is pertinent in supporting traffic movements and good joint between layers. Control of F–T and chemical reactivity of hydraulic cement–pozzolan aggregates are tantamount to resist crack potential. Therefore, what is studied of CVC materials is directly relevant for RCC. With RCC, the analytical interest is more on composites rather than in a singular form. It is vital to understand the deformation and early and long-term properties in order to balance the internal and external forces.

6.2.2 RCC for Pavement Systems and Hydraulic Structures

Table 6.2 compares RCC as material and construction technology while providing an overview of the basic differences in terms of the nature of applications and hence the loading and design considerations. In a nutshell, the points that differentiate the RCC for pavement application from that for dams are that RCCP is subjected to abrasion and has higher binder content.

6.2.3 Paste Content as a Basis

Especially in RCC for hydraulic systems, a classification system based on the paste content and associated construction methodology has evolved, especially in RCC for hydraulic systems. Herein, paste involves the sum total of cement, pozzolans, water, admixtures, aggregate fines, and small air bubbles, essentially everything below 75 µm. As RCC was being researched, three major paths [13] evolved:

1. The lean concrete option based on soil technology was developed by USACE.
2. High-paste RCC was developed by British engineers; the associated method could be considered as a hybrid of conventional concrete mix design and earthfill dam construction methods.
3. The Japanese evolved what is known as rolled concrete dam (RCD).

TABLE 6.1
Synoptic Comparison between CVC and RCC

SN	Basis	CVC	RCC
Materials	Cement content	Decided by the water demand of the aggregate system and w/c ratio of the mix Relatively higher for a given strength	Decided on % by weight basis required to achieve specified strength; fly ash and/or other binders is/are mostly used; relatively lesser for comparable compressive strength.
	Aggregate grading	Comparatively less well/more openly graded	Very well graded/closely to minimize voids.
	Moisture content	Given by w/c ratio by weight	Optimum moisture content (OMC)
	Chemical admixtures	Primarily retarders, water reducers, air entraining agents, viscosity modifying agents	Mostly, retarders in hydraulic structures; none in pavement structures.
Workability	Consistency measurement	Can be measured by slump test, compaction factor, flow, etc.	Vebe consistometer; value depends on the surcharge weight used.
	Theoretical density (NMSA,19 mm)	Usually close to or greater than 98% depending on mix constitution	Usually close to or less than 98% depending on the mix proportioning method; could range between 95% and 98%
Mixing/transport	Concrete mixer types	Drum, pan, twin shaft horizontal, transit	Drum, pan, twin shaft horizontal, continuous flow, transit, pug mills depending on the application.
	Mixing energy required	Relatively lower	Relatively vigorous
	Transportation	Dump trucks, transits	By scraper, conveyor belts, bottom and rear dump trucks or large front end loaders.
Construction field checks	Spreading and laying	Bob cat, concrete pavers	By back hoe, loader, asphalt pavers, concrete pavers, dozers, etc.
	Compaction	Usually using internal or external vibrators	Vibratory, rubber tire rollers
	Density checks	Not required on fresh concrete	Required on fresh concretes
	Fresh concrete specified in terms of	Slump, air content, and temperature	Vebe, OMC, and maximum fresh (dry) density

(*Continued*)

TABLE 6.1 (CONTINUED)
Synoptic Comparison between CVC and RCC

SN	Basis	CVC	RCC
Mechanical and durability properties	Strength	Relatively lesser for the same cement factor	Relatively more for the same cement factor
	Surface finish	Smooth	Rough and wavy due to roller compaction
	Air Entrainment for	Required; relatively easier to entrain	May or may not be required Quite difficult to entrain at regular doses
	Shrinkage, carbonation, sulfate resistance, freeze–thaw resistance, alkali silica reactivity, abrasion resistance	Widely studied and reported in the literature and quite conclusive	Not much studied to be conclusive to report

TABLE 6.2
Sampling of Comparison between RCC for Pavement and RCC for Hydraulic Structures Applications

SN	Basis	RCC Pavement Systems	RCC Hydraulic Systems
Applications	Areas	Pavement bases, two-lift or composite pavements, wearing courses, low maintenance roads, parking areas, industrial access roads, inlay rehabilitation, city streets, shoulder reconstruction, airport aprons	Gravity dams, dam rehabilitation, cofferdams, new spillways, downstream buttress, overtopping protection works, upstream slope protection, erosion protection, dam foundation improvement, central core construction.
Design and specs	Characteristic strength	Flexural and compressive strength, usually at 28 or 56 days	Compressive strength usually no less than 90 days (small structures) and upto 3 years (large structures).
	Important mechanical properties	Spilt tensile (occasionally)	Spilt tensile, direct tensile, shear strength, elastic modulus, creep, shrinkage, Posisson's ratio.
	Key durability properties	Abrasion resistance, freeze–thaw	Permeability, erosion resistance, thermal properties.

(*Continued*)

TABLE 6.2 (CONTINUED)
Sampling of Comparison between RCC for Pavement and RCC for Hydraulic Structures Applications

SN	Basis	RCC Pavement Systems	RCC Hydraulic Systems
	Contraction joints	Longitudinal and/or transverse joints are provided only when required and depending on the application	Subject to the RCC design principles, the structure is treated monolithically allowing it to settle on its own; otherwise transverse joints at predetermined intervals along the length of a dam are induced during construction phase.
Materials and systems	Binders	Ordinary Portland cement, Portland pozzolana cement, slag, fly ash, silica fume; combination usually selected depending on the required properties	High volumes of fly ashes (>60%) + ordinary Portland cement, slag, natural pozzolans.
	Aggregates	Relatively openly graded with maximum size restricted up to 20 mm; amount of fines is relatively less important	Closely graded usually with maximum size up to 75 mm; amount of fines is critical.
	Chemical admixtures	Usually no admixtures are used	Mostly retarder to ensure continuity of construction and monolithic nature of structure.
	Important systems	Paver machine and compaction	Aggregate production, temperature control, consistent batching, compaction, curing.
Mixing/ transport	Concrete mixer types	Drum, pan, twin shaft horizontal, transit	Forced action mixers (horizontal twin shafts), pug mills and in some cases rotating drum type mixers are common to achieve batch to batch consistency of RCC.
	Conveying	Dump trucks, transits	Mostly by conveyor belt of continuous conveying systems part transit and part belt conveyor have also been employed.
Construction	Spreading and laying	With bob cat, concrete pavers; 200–300 mm thick application-dependent layers over subgrade/base	With dozers, pavers (used only when paved layer exist); 150–300 mm thick horizontal layers laid in continuity to avoid vertical joints between two layers; concrete setting retarded for monolithic construction.

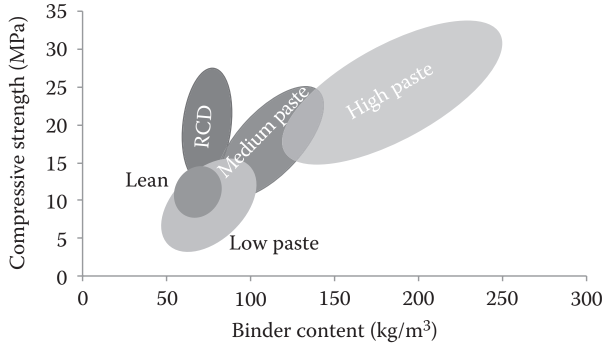

FIGURE 6.5 RCC variants according to design philosophies. (From Andriolo, F R, *The Use of Roller Compacted Concrete*, Saõ Paulo, Oficina de Textos, 1998; ACI Committee 207, *Report on Roller-Compacted Mass Concrete*, Farmington Hills, MI, ACI, 2011; Hansen, K D and Reinhardt, W G, *Roller-Compacted Concrete Dams*, New York, McGraw Hill, p. 298, 1991; Nagataki, S et al., State of art of RCD dams in Japan, Salvador, Bahia, Brazil, IBRACON, First Brazilian International RCC Symposium, 2008; Schrader, E, Roller compacted concrete aggregates and mix designations, ICAR, 7th Annual International Center for Aggregates Research [ICAR] Symposium, 1999.)

The choice of a pathway is dependent on many factors, and human experience plays a crucial role in such decision making. With sustainability becoming increasingly important, any choice must be more deliberate than before. In order to appreciate the potential sustainable footprint that each of these options could offer, see Figure 6.5 [14,15]. Detailed descriptions, applications, and case histories are available in the published literature.

6.2.4 From Pavement Perspective (RCC–Pavement-Quality Concrete–Self-Consolidating Concrete)

Figure 6.6 shows a quantitative comparison of self-consolidating concrete (SCC), pavement-quality concrete (PQC), and RCC. These data are taken from published literature in recent years and show the averages of water and paste volumes in each of these types of concretes. As compared to SCC and PQC, RCC is a much drier system in terms of water content. Moreover, the paste content is also lower than the other two concretes. Additionally, as the consistency of the concrete type increases, higher amounts of water-reducing admixtures are used. The use of such admixtures is next to negligible in RCC and is highest in SCC.

Although the paste volume in RCC is relatively lower, and no water reducers are usually used, the strength of this type of concrete is comparatively higher when compared to SCC. Inversely, for a given strength, the amount of paste required by RCC is much less than that required by SCC. Researchers [16] are trying to establish the viability of SCC for pavement applications. Looking at RCC as an alternative for pavement applications, while overcoming some of the potential limitations, seems to be a more sustainable option than the others. This needs to be critically accounted for during the project conceptualization, construction, and the performance of the pavements.

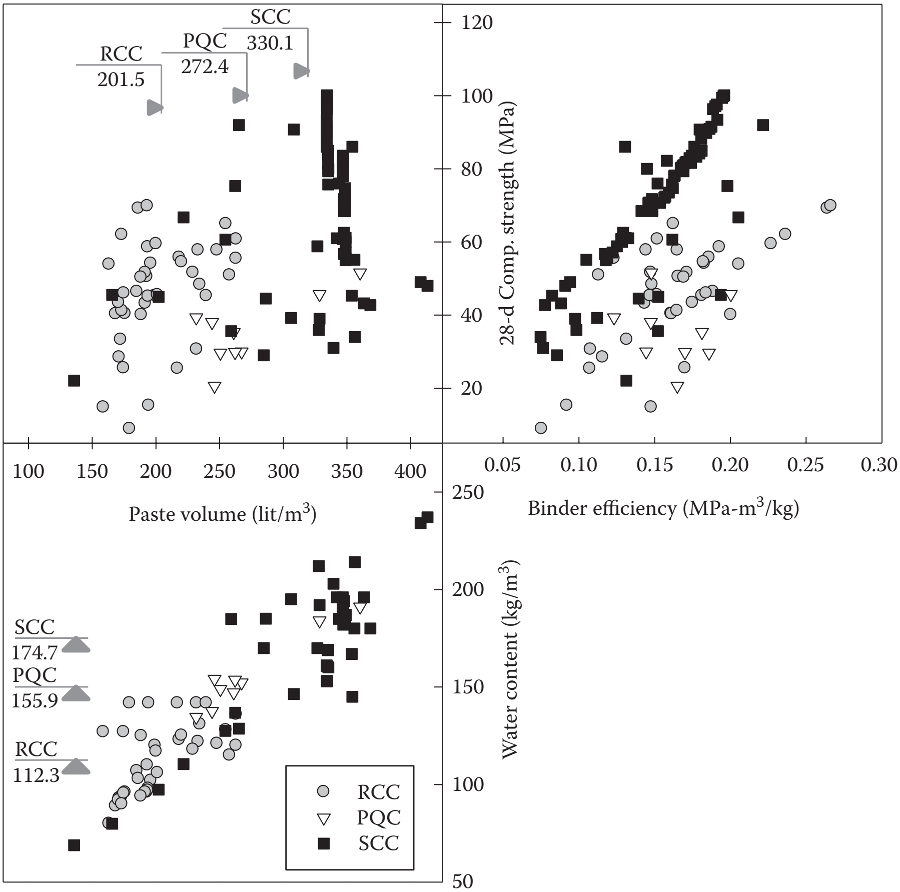

FIGURE 6.6 Comparison between SCC, PQC, and RCC—paste volume, strength, and water content.

6.2.5 RCC-Conventional Dam Concrete

Figure 6.7 shows a synoptic comparison of strength and binder contents for two types of dam construction methods viz. RCC and conventional block method with CVC [17]. The following points need to be carefully analyzed:

- With the advent of PPC, slag, and other pozzolans, dam engineers prefer these (in combination with OPC) over OPC for CVC dams. There is a growing trend of such usage with variations in the (90 days to 1 or 2 years) age at which concrete is characterized. Previously, mostly 90-day strength was specified for concrete characterization, often limiting the sustainability footprint of CVC dams.
- RCC dams almost invariably specify strength at later ages, even up to 3 years. The use of pozzolan and/or fly ash is either specified or arranged for.

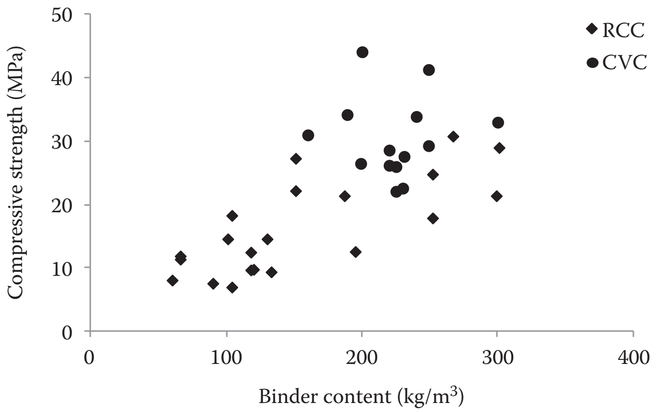

FIGURE 6.7 Comparison of RCC and CVC dams with strength at 90 days. (From ACI Committee 207, *ACI Manual of Concrete Practice 207.1R Guide to Mass Concrete*, Farmington Hills, MI, ACI, 2005; ACI Committee 207, *Report on Roller-Compacted Mass Concrete*, Farmington Hills, MI, ACI, 2011.)

- The use of pozzolan in RCC has varied between 0% and 80% of the total binder, with no universal optimum. RCC derives strength benefit from its long-term characterization. See Figure 6.8 for a sampling of strength gain at 365 days for some RCC mixtures [18].
- All variants (design philosophies) of RCC offer a sustainable alternative material. As a construction technique, the savings achieved for various reasons contribute to national savings both monetarily and due to early completion of the project. Early completion of the project, in turn, leads to early commissioning of projects thus ensuring early revenue generation.

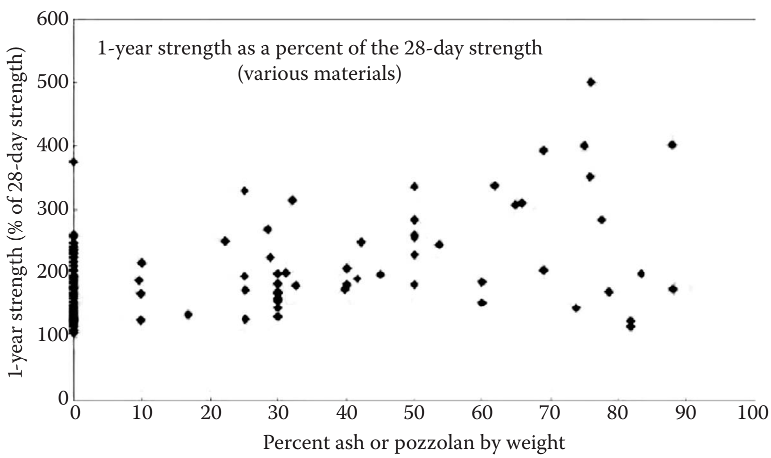

FIGURE 6.8 Efficiency of cementitious material as a function of pozzolan. (From Schrader, E K, Roller compacted concrete. In *Concrete Construction Handbook*, [ed.] E G Nawy, Boca Raton, FL, CRC Press, pp. 20.1–20.76, 2008.)

6.3 MATERIAL CONSIDERATIONS

Materials have a major impact on all other life cycle phases, as they often provide project-level constraints during the design phase and strongly influence the construction, preservation/rehabilitation, and reconstruction/recycling phases and even impact the operational phase [19]. Computing the environmental impact of materials and construction activities is a complex activity and involves multidisciplinary knowledge. From a sustainability point of view, materials have to be considered from the following perspectives:

- Material sources
- Material processing, including production
- Construction and operational performance during lifetime
- Preservation and rehabilitation
- Reconstruction and recycling

At every stage of production, utilization, demotion, and recycling and reuse, there is energy involved; but this is rather a myopic approach in understanding the sustainability of any material. Although in its infancy, some understanding regarding concrete sustainability exists; there is some growing knowledge about the sustainability of concrete pavements [19]. There is, however, a lack of structured body of knowledge regarding sustainability in construction of hydraulic structures. Dams usually have longer design life, are massive structures, are designed with greater factor of safety, are rehabilitated multiple times during their performance period, and have wider implications on society and the environment as well.

In the conventional block method of dam construction, usually either OPC or low heat of hydration cements, or PPC is specified. Although recent trends in material specifications show a leaning toward the use of other pozzolans, it is interesting to note that the Japanese method of RCD uses much less cement. Figure 6.9 shows a comparative trend between the block method of construction and RCC [20]. In Brazil, RCC is generally produced using about 70 to 140 kg/m^3 of binders (OPC, fly ash, pozzolan, or blast furnace slag) [21]. In Spain, on the other hand, medium-paste RCC mixtures are used with an average binder content of 200 kg/m^3 (roughly 50% OPC and 50% fly ash) [22]. In other parts of the world that follow medium- to high-paste mixture philosophy, in general, there seems to be a recent trend in using mixtures with paste contents in the range of 21%–23% [18] by volume. A survey in 2002 indicates that close to 47% of the dams built across the globe are based on high-paste-content RCC, followed by medium-paste (18.6%), RCD (15.4%), lean (16.1%), and hard filled (1.4%) [23].

Depending on the application of RCC in a pavement system, the binder content varies anywhere between 100 and 350 kg/m^3. Fly ash, slag, and silica fumes have been used in many applications to varying degrees.

In either application, binders and mixture proportion are primarily a result of the mixture design philosophy used and past experience. A detailed discussion on this is beyond the scope and focus of this chapter.

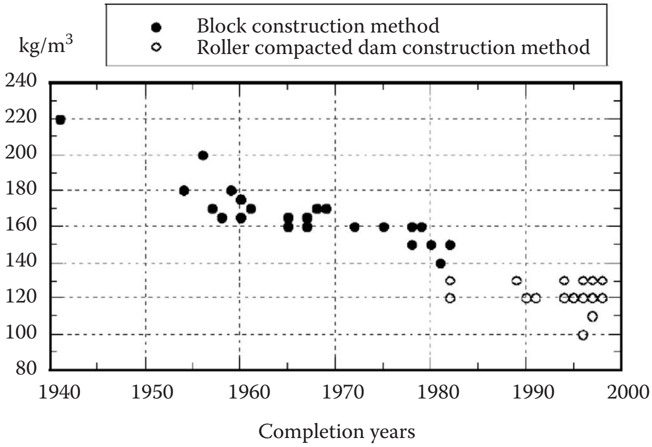

FIGURE 6.9 Change of cementitious material content in Japan. (From Uji, K, *Roller Compacted Concrete Dam and Utilization of Fly Ash in Japan*, Ho Chi Minh, The JSCE–VIFCEA Joint Seminar on Concrete Engineering, 2005.)

Finally, it is important to appreciate sustainability at a broader level. While sustainability on one hand means "just usage," on the other hand, it also means preservation for future. On large-scale projects, there are invariably conflicting issues with the "right quality" and at the right price. Contractors are often offered rewards for early completion of projects, but they are rarely rewarded for the sustainable selection of materials. This may involve supporting additional costs for getting more sustainable options, preserving invaluable natural resources, and evolving innovative ideas for using local materials.

6.3.1 Binders

The principles of binder selection for pavement and hydraulic applications of RCC are different. This primarily originates because of the differences in the loading, rate of loading, and application of either structure. For example, a pavement is usually expected to perform at the earliest, sometimes within 24 h; comparatively, dams in general are designed for lower stresses (quantitatively), which are usually experienced not before 1 year [17]. Moreover, as indicated in Table 6.2, the characteristic requirements of these concretes are different for both the applications. Another important consideration is the characterizing age of concrete, which is relatively earlier (28 days) for pavement structures as compared to hydraulic structures (>90 days). In terms of durability, the requirements are again different. For example, abrasion resistance is important in pavements, whereas erosion resistance and permeability are important for hydraulic structures. All these factors have definite effects on the binder selection. In addition, the "volume game" plays a vital role in selection of a binder system. For pavement systems, usually the volume of RCC in a project is comparatively much lesser than the (continuously increasing) volumes of hydraulic structures/dams.

In general, RCC can be manufactured with any of the basic types of hydraulic cement or a composite of hydraulic cement and pozzolan. Depending on the application and durability, the selection of a suitable binder system is made. The selection of binders (composition and quantity) is governed by constructability, strength requirements, exposure conditions, economics, and availability.

For conventional concrete pavement applications, the usual binder content ranges for wearing courses could be 300 ± 30 kg/m^3 [24]. When applied to pavement bases, the binder contents would be much lower. Due to construction requirements, the dry nature of concrete, inadequacy of sufficient fines in local materials (especially fine aggregates), and economics, the use of pozzolans and other supplementary cementitious materials is encouraged. Composite systems can include OPC with fly ash (Class C or F), slag, or other pozzolans [25]. Mixes with fly ash are frequently used in some countries, sometimes exceeding 50% of the binder quantity [24]. Use of rice husk ash is also possible [26–28]. The use of other binders in higher volumes can be encouraged where environmental regulations restrict the use of fly ash in concrete. It should be noted that the percentage of cement replacement with materials like fly ash and slag that can be comfortably controlled in RCC is usually slightly higher than that for conventional pavement concrete. Use of pond ash with high carbon content has also been researched [29]. Use of silica fume or silica fume-blended cements has been encouraged in Canada [30], Sweden, Norway, Denmark, and Australia [24] for better F–T and frost resistance. The adaptability of RCC to various binder systems, while remaining cognizant of locally available binder sources, makes it a more sustainable option.

In the case of RCC for dam construction, the selection of binder systems, apart from the technical requirements, is governed by the availability and associated logistics. Another factor, heat of hydration, plays a decisive role in the selection of binder systems. Apart from OPC (low heat, sulfate resistant) alone, PPC and Portland slag cement have been used [3]. Mostly for medium- to high-paste mixtures, various composite systems have been used. Either factory- or site-blended composite systems have been used. A well-crafted quality assurance system for factory-blended binder systems reduces the cost of quality at the site besides having a better control. Pozzolan varying from none to 80% by mass has been used primarily with the following objectives:

1. As a partial replacement for cement to reduce heat generation
2. As a partial replacement for cement to reduce cost
3. As an additive to provide supplemental fines for mixture workability and paste volume [3,18]

RCC for dams are also adaptable, and a range of pozzolanic materials have been successfully applied. Figure 6.10 reflects the same [31]. The important point is that RCC does not follow the same rules and trends as conventional concrete with regard to optimum cementitious and pozzolan content. Each project should be evaluated on its own merits, with its own materials, and with a wide range of options during the initial investigations. Open mindedness on the part of decision makers is essential.

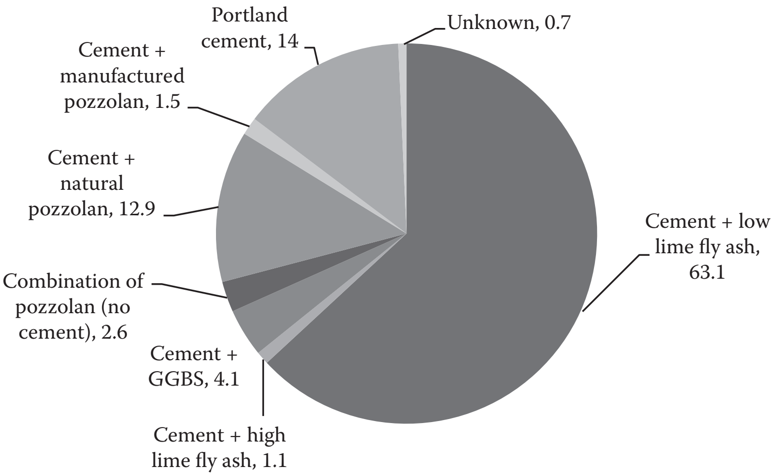

FIGURE 6.10 Cementitious materials used in RCC dams either completed or under construction till 2002. (From Ghafuri, A G et al., Trial mix programme for Jahgin dam—The first major RCC dam in Iran. In *Proceedings of the IV International Symposium on Roller Compacted Concrete Dams, Madrid, Spain* [ed.] L Berga et al., CRC Press, November 17–19, 2003.)

They should not be misled by old traditional concrete experience or guidelines or experience with only one type of RCC [18].

6.3.2 Aggregate Systems

Aggregate sourcing, processing, handling, and usage are some of the critical challenges while constructing rather intensive, faster, and voluminous RCC dams but not so much for pavement systems. Although basic principles of aggregate selection remain more or less the same, the following sections highlight some key points more from the sustainability perspective. Primarily, in RCC, the aggregates form a skeleton, and the paste fills the voids, with the excess paste rising to the top during roller compaction. Especially in leaner and medium-paste RCC mixtures, the consistent and closed grading of aggregates with enhanced fine content is relatively more important than in CVC.

For pavement systems, continuous aggregate grading and enhanced need for fines (passing through a 150-μm sieve) are required. However, for wearing course applications, higher binder contents compensate for the fines to a great extent rendering aggregates meeting respective national standards as acceptable for RCC. Where leaner RCC mixtures are used, the importance of fines is enhanced. The MSA usually specified is between 16 and 19 mm and could go up to 25 mm; this is done for reducing segregation, allowing for thinner layer placement and for giving relatively smooth surface texture [32]. Use of marginal materials has also been tested [33,34]. Figure 6.11 shows generally acceptable combined aggregate grading bands for both

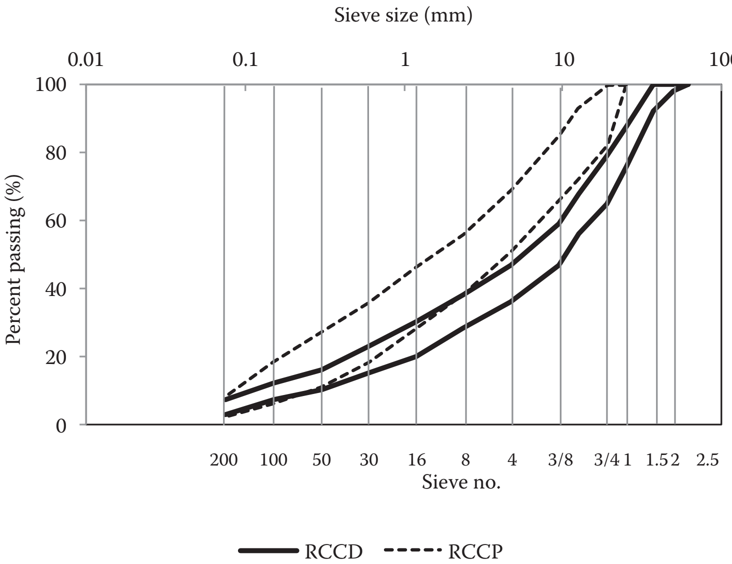

FIGURE 6.11 Combined aggregate grading for the two RCC applications. Note: Maximum sizes of aggregate (MSAs) are different. (From ACI Committee 211, *ACI 211-4R-08: Guide for Selecting Proportions for High-Strength*, Farmington Hills, MI, ACI International, 2008; Schrader, E K, Roller compacted concrete, In *Concrete Construction Handbook*, [ed.] E G Nawy, Boca Raton, FL, CRC Press, pp. 20.1–20.76, 2008.)

applications. In the case of pavement applications, the combined aggregate grading is quite similar to that required for making asphalt cement concrete [35].

For dam construction, the sourcing of aggregate-making material is critical and has serious economic impacts. The sources available could include crushed and uncrushed river alluvium material, quarried rock, tunnel muck, or a combination of these. Apart from the environmental impact that any dam construction has, the mineralogy of raw materials for aggregate production has to be more carefully accessed for its potential to impact the properties of RCC. A wide variety of aggregates including gravel, material from dirty quarry, overburden from quarry, decomposed rocks, and oil shale have been successfully used; each project must, however, be evaluated on a case-to-case basis to find the best suitability of available aggregate sources vis-à-vis envisaged design [15].

The production of aggregates through crushing and screening is another critical activity that requires very close monitoring of the complete process, including waste generation. Control is primarily required for consistency of produced aggregate gradings and for managing the product breakups. The number of product fractions to be produced should be carefully restricted to a minimum. Crusher optimization is an essential feature of an RCC project; the fabric of sustainability needs to be carefully crossed over with the initial direct savings. Wastages could originate during the initial screening, production, and handling and rehandling. This complete process of aggregate production and handling is a money spinner, which clever contractors tend to embark upon very swiftly. Often in the shining light of immediate monetary savings, sustainable savings are overlooked.

Another point worth nothing is the MSA that is used in RCC, as lowering MSA increases the crushing cost. Figure 6.12 shows a comparison of MSA as used in conventional dams and for RCC. This figure is compiled from the cited references. The MSA used in the RCD concept in Japan is up to 120–150 mm [2,20,36]; the advantages cited include reduced wastage and improved strain capacity, while segregation is cautioned [2]. In other philosophies of RCC design, earlier RCC projects tended to use 75-mm MSA, but recent trends are moving more toward the use of 50-mm MSA [15]. This reduces equipment maintenance and segregation and improves lift joint quality [18].

MSA has a definite impact on the sustainability footprint of concrete in general. MSA is attributed to density (being used in gravity dams); a larger aggregate, i.e., size, occupies larger space, hence reducing the volume of the material required to be exploited. With the factor of safety for dams getting higher especially for structures that have to be built in seismically affected zones, the lift joint performances were scrutinized even more vis-à-vis better permeability coefficient.

Optimizing (instead of the term "lower") cement content for RCC is an imminent step toward reducing the thermally induced stresses. Alternatively, the combination of supplementary materials such as pozzolanic fines is simply a matter of choice. Even after lowering MSA, the poor performance of RCC has not been completely eliminated. It is not only the job of high paste from RCC that is responsible, but also other intrinsic components starting off with the geology, exploitation, crushing, stockpiling, cooling, conveyance, etc., will have to be inculcated in the broader sense of the equation. From the construction point of view, MSA affects segregation and compactability of a mixture; both these factors have a direct impact on the performance of dams.

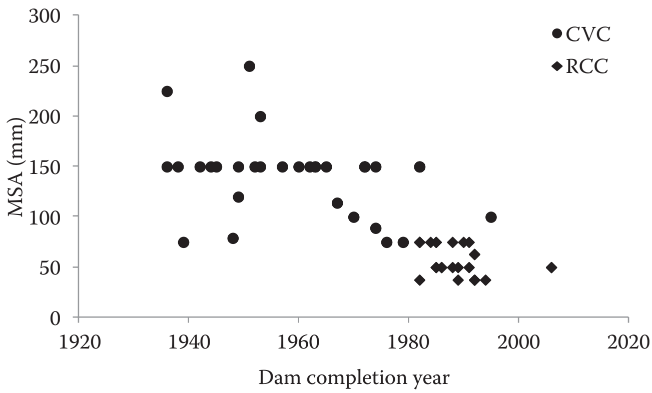

FIGURE 6.12 Comparison of MSA as used for CVC and RCC. (From ACI Committee 207, *Report on Roller-Compacted Mass Concrete*, Farmington Hills, MI, ACI, 2011; *ACI Committee 207, ACI Manual of Concrete Practice 207.1R Guide to Mass Concrete*, Farmington Hills, MI, ACI, 2005.)

The requirement of fine (for filling finer voids) content depends on the design philosophy adopted and on whether the fines are plastic or nonplastic; limits and specifications for optimal performance could be derived based on the nature of fines [18]. For lean mixtures, ideally the range of fines passing 75 μm is between 5% and 8%. More fines should be cautiously evaluated depending on their plasticity, ability to impact water demand, mixing, compaction, and performance [3,13]. These fines could come either from fine aggregates or added pozzolan.

Another important aspect that has a sustainability impact, especially in areas with higher temperatures is the cooling of aggregates, which is an energy-intensive activity. Cooling of aggregates is essential for lowering the temperature rise and hence avoids thermal cracking. Value engineering should be utilized to reduce as much as possible the energy consumption for such activity.

Recycled concrete aggregate would soon pose itself as an inevitable option for concrete making. Using recycled pavement concrete and other concretes has been researched for RCCP [37,38]. The question that arises for the dams constructed now is whether these dams will have the potential to be recycled in any way or not. It is believed that there will come a time when other sources of energy will be on par with hydropower. At that juncture, the recycling itself would become a serious cost to consider.

6.3.3 Admixture Systems

The use of chemical admixtures in RCC is application dependent. For pavement applications, the use of routine chemical admixtures like water reducers and retarders is not widely accepted in RCC. The need for using chemical admixtures either to reduce water or for retarders was not felt earlier primarily because RCC can retain water enough for roller compaction. The effects of various chemical admixtures have been recently studied [4]. While the use of air-entraining admixtures is encouraged in North America for enhancing F–T resistance, the development of an adequately spaced entrained air void structure in the paste can be problematic because of the dry, stiff consistency of the paste. Due to the inherent nature of mixing, placing, and compacting RCC, both irregularly shaped and spherical air voids of various sizes and distributions are left behind in the internal structure of hardened RCC (Figure 6.13). Both these types of air voids may lend some F–T resistance to RCC, in certain circumstances. However, the lower permeability inherent in high-density RCC likely contributes to the F–T resistance as well. The spatial distribution, size grading, and shape cannot be controlled well. An indirect way of regulating these, however, is by having strict control over the combined aggregate grading and water content of the mixture. These compaction voids can play some role in enhancing the F–T resistance of concrete; however, the use of an air-entraining agent definitely improves concrete's resistance to freezing and thawing [30,39]. There is, however, disparity between the laboratory results and field observations. Some of the RCCP without any air entrainment have withstood the test of time in North America. Care and detailed prior testing of material are strongly recommended before any such applications. The F–T response of a mixture is an outcome of individual materials' behaviors as well.

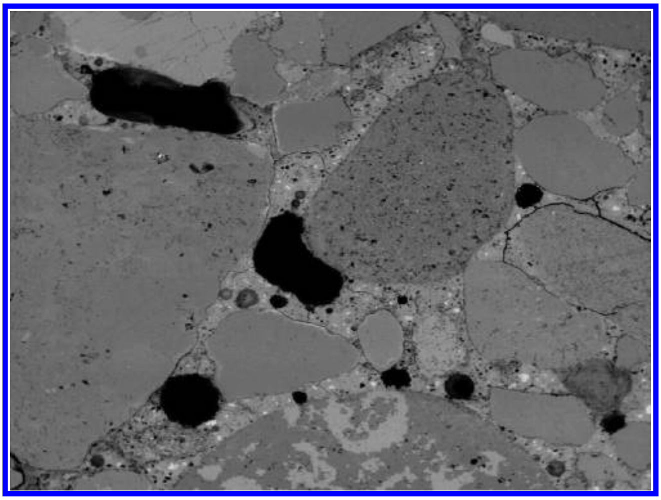

FIGURE 6.13 Irregular shape compaction voids (darker areas) in scanning electron microscope.

With regard to RCC for dam construction, set-retarding admixtures are most widely used, especially for avoiding cold joints between subsequent layers during construction. Water-reducing admixtures have been used in some countries [2]. Use of air-entraining admixture has been very limited due to the potential difficulty of entraining and distributing the air bubbles in the mixtures. Reports indicated that entraining air reduces the water demand of the mixture up to 12% [40] with respect to control mixture and improves the freezing–thawing resistance of hardened concrete [41].

6.3.4 Deriving Local Sustainability

Effective engineering use of local resources, while meeting the construction specifications, is a big, yet surmountable, challenge; it may, however, not be possible every time. For RCCP, the use of recycled, substandard, or marginal materials should be carefully studied beforehand. With regard to RCCD, apart from quality considerations, the choice of materials is primarily governed by volumes, assured continuity of supply of materials, and economics. Any natural material once consumed cannot be restored back in its position; at most, it could be recycled. RCCD permits use of higher volumes of fly ash; on some projects, processed pond ash has also been used. Many times, the use of fly ash is restricted because of long hauling distances or stringent prescriptive specifications.

Construction specifications play a vital role in effective usage of materials. Unnecessarily stringent specifications could not only lead to environmentally and economically expensive resource consumption but also increase the construction cost and energy expenses. Other barriers for developing cementitious materials with locally available materials include non-availability of appropriate technology, resistance to change, and nonconsideration of such options during the project development stage. An integrated approach is hence essential, at least in major projects. Designers, engineers, and contractors should be encouraged and incentivized to devise strategies for better usage of local materials and construction innovation.

RCC is both a material and construction method; hence, just having a sustainable material is not enough—the construction method has to follow suit. Any construction method that costs time also costs money. For example, an RCC concept that is qualitative, simple, and faster to construct requires lesser equipment (by using them efficiently); conveyance reduces fleet logistics, all of which runs on fossil fuel, let alone greening the environment.

6.3.5 Mixture Proportioning

With regard to pavements, since RCC has its origins in soil analogy, there are two schools of thought according to which the concrete mixture proportioning is performed. The first school proportions RCC mixtures using the soil analogy compaction method, while the second school uses the conventional water/cement (w/c) ratio and consistency approach. The details of these methods can be found in the literature [25]. Irrespective of the approach taken, subsequent to lab trials and full-scale trials, certain field adjustments are invariably required. Table 6.3 offers a sampling of RCCP mix proportions.

RCC suitable for use in dams can be made with very low cementitious contents, on the order of 50–88 kg/m^3 (85–150 lb./yd.^{3}), or it can be made with very high cementitious contents, on the order of 118–252 kg/m^3 (200–425 lb./yd.^{3}). Both options, plus intermediate cementitious contents, have been used quite successfully on low and high dams; both options continue to be popular, and both are expected to be used in the future. Table 6.4 shows a sampling of RCC mixture proportions used for various dams. The decision-making process for selecting the type of mix is not very dependent on the size or height of the dam. Unfortunately, it is often more related to the simple issue of what the designer or owner has used in the past. The decision should be based on factual information related to foundation quality; the degree of reliable inspection expected; facing techniques; climate, cooling, and thermal issues; the age at which the reservoir will be filled; and available materials with their associated costs and quality. The best overall option might be a higher-strength, high-cementitious-content mix with less mass in one situation, but it could be a lower-strength, low-cementitious-content mix in another [18].

An analysis based on the data from the dam database [42] is presented as follows. The design philosophies used in various parts of the world vary. Figure 6.14 presents a histogram of the binder contents used from 447 dam mixtures around the world, whereas Figure 6.15 shows the range of binder contents used in various countries, which shows a wide scatter and variations in the practices.

TABLE 6.3
Sampling of RCCP Mixture Proportions

Ref.	Cement (kg/m³)	Fly Ash Type	Fly Ash Content (kg/m³)	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Additive (kg/m³)	Remarks
[43]	325	NA	–	138	1341	599	0.81	Conventional pavement concrete
	256	NA	–	104	1241	936	0.64	
[44]	154.25	C	154.25	107.98	955.17	955.17	NA	Austin, TX
	237.31	F	125.77	121.62	1059	869.15		Ft. Campbell, KY
	237.31	F	88.99	113.91	1121.29	919.58		Spring Hill, TN
[45]	178	C	178	131	1146	712		Port Washington Power Plant, WI
	220	C	95	138	1127	1177		Pullicum Power Plant, WI
[30]	296	NA	–	102	1347	747	1.2	Silica fume cement
	246	NA	–	107	1355	758	1	
[46]	300	C	60	105	1000	1015		AEA 1000 ml/m³ + water reducer 960 ml/m³
	250	NA	–	90	1070	1130		
	300	NA	–	105	1000	1075		
[47]	198.5	C	47.5	117.1	1038.9	1018.4		
[48]	106	F	177	118.6	1246	831		High volume fly ash application
	133	F	221	106.2	1204	802		
[29]	125	F	152	141	1247	789		High volume use of pond ash
[33]	160			152	1275	845		RCC for base applications; with marginal aggregates
[49]	160	NA	–	130	1285	931	1.6	RCC for base applications or composite pavements
	118	F	62	122	1341	876	1.8	
	105	F	85	122	1384	830	1.9	
	100	F	120	120	1496	704	2.2	

TABLE 6.4
Sampling of RCCD Mixture Proportions (Compiled from [42])

Name	Country	Type	Purpose	Dimensions: Height (m)	Dimensions: Length (m)	Volumes: RCC (× 1000 m³)	Volumes: Total (× 1000 m³)	Binders: Cement (kg/m³)	Binders: Pozzolan (kg/m³)	Binders: Total (kg/m³)
Urugua-i	Argentina	Gravity	H	77	687	590	626	60	0	60
Paradise (Burnett River)	Australia	Gravity	FI	50	940	400	400	63	0	63
Santa Cruz do Apodi	Brazil	Gravity	FIRW	58	1660	1023	1120	80	0	80
Bandeira de Melo	Brazil	Gravity	IW	20	320	75	87	70	0	70
Salto Caxias	Brazil	Gravity	H	67	1083	912	1438	80	20 (F)	100
Canoas	Brazil	Gravity	W	51	116	87	93	64	16 (N)	80
Karebbe	Indonesia	Gravity	H	73	216	195	250	80	0	80
Nagashima	Japan	Hardfill		33	127	23	55	40	50 (S)	90
Nueva Italia	Mexico	Gravity	I	90	375	367	451	65	0	65
Willow Creek	USA	Gravity	FR	52	543	331	331	47	19 (F)	66
Zintel Canyon	USA	Gravity	F	39	158	54	55	74	0	74
Changshun	China	Gravity	HW	69	279	170	200	134	89 (F)	223
Shimajigawa	Japan	Gravity	FIW	89	240	165	317	84	36 (F)	120
Shimagawa	Japan	Gravity	FW	90	330	390	516	84	36 (F)	120
De Mist Kraal	South Africa	Gravity	IW	30	300	35	65	58	58 (F)	116
Elk Creek	USA	Gravity	F	35	365	266	348	70	33 (F)	103
Taum Sauk	USA	Hardfill	H	49	2060	2448	2500	59	59 (F)	118

(*Continued*)

TABLE 6.4 (CONTINUED)
Sampling of RCCD Mixture Proportions (Compiled from [42])

				Dimensions		Volumes		Binders		
Name	Country	Type	Purpose	Height (m)	Length (m)	RCC (× 1000 m³)	Total (× 1000 m³)	Cement (kg/m³)	Pozzolan (kg/m³)	Total (kg/m³)
Guanyinge	China	Gravity	FHIW	82	1040	1240	1815	91	39 (F)	130
Enlarged Cotter	Australia	Gravity	W	82	350	369	400	70	120 (F)	190
Shuikou	China	Gravity	FHI	101	791	600	1710	60	110 (F)	170
Belén-Cagüela	Spain	Gravity	F	31	160	24	29	73	109 (F)	182
Boqueron	Spain	Gravity	F	58	290	137	145	55	130 (F)	185
Olivenhain	USA	Gravity	W	97	788	1070	1140	74	121 (F)	195
Portugues	USA	Arch-Gravity	F	67	375	270	279	121	55 (F)	176
New Victoria	Australia	Gravity	W	52	285	121	135	79	160 (F)	239
Maroño	Spain	Gravity	W	53	182	80	91	80	170 (F)	250
Los Morales	Spain	Gravity	W	28	200	22	26	80	140 (F)	220
Son La	Vietnam	Gravity	FH	139	900	2677	4800	60	160 (F)	220
Xiao Yangxi	China	Gravity	W	45	118	47	49	138	113 (F)	251
San Lazaro	Mexico	Gravity	FGW	38	176	35	53	100	220 (M)	320
Upper Stillwater	USA	Gravity	IW	91	815	1125	1281	79	173 (F)	252
Dinh Binh	Vietnam	Gravity	FHIW	55	571	183	430	70	175 (F)	245

Note: F: flood control; H: hydropower; I: irrigation; R: recreation; W: water supply.

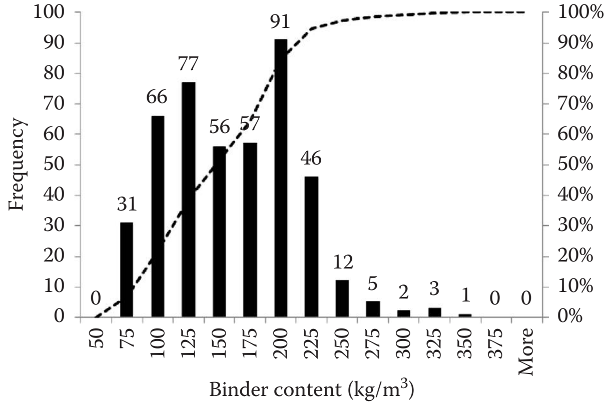

FIGURE 6.14 Dams by binder contents. (From Malcolm Dunstan & Associates. Dam database. *Malcolm Dunstan & Associates*. [Online] Available at http://www.rccdams.co.uk [Accessed July 31, 2014].)

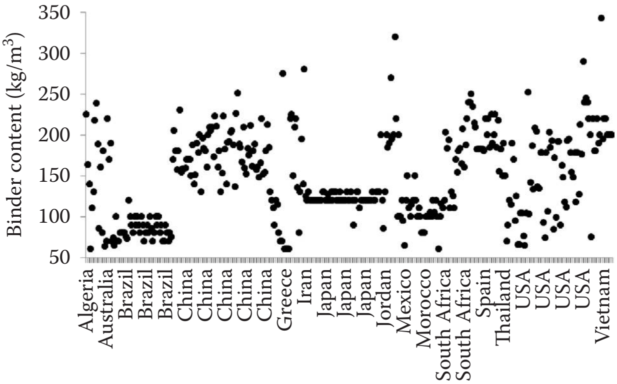

FIGURE 6.15 Binder contents by country. (From Malcolm Dunstan & Associates. Dam database. *Malcolm Dunstan & Associates*. [Online] Available at http://www.rccdams.co.uk [Accessed July 31, 2014].)

6.4 RCCD-CONSTRUCTION METHOD

This section covers a synoptic review of RCC as a construction method while deriving points of distinction between the two applications. In both the applications, full-scale trials are essential; these are very helpful in imparting training, benchmarking material and equipment performances, appreciating time-cycle requirements, and as precursors to tracking the properties of concrete. Sometimes, these trials also prove vital in researching certain unforeseen value engineering, which could change the resource requirements or financial implications. At times, such multiple full-scale trial embankments or pads are constructed to fully appreciate the RCC process. Figures 6.16 and 6.17 show two such examples. Emphasis on careful work planning vis-à-vis weather is an integral part of RCC construction, more so in case of dams [50,51].

RCC dam construction is an equipment-intensive process. When compared to conventional dams, RCC typically has a lower ratio of labor hours to volume placed, primarily due to the use of mechanical equipment for spreading and compacting the mixture, less forming, and reduced joint cleanup. With developments such as sloping layer method and GERCC, the placement rates of RCC have further markedly increased [3].

FIGURE 6.16 Full-scale test sections. (From Rizzo, P C et al., Saluda dam remediation RCC mix design program, USSD. USSD Annual Conference, Charleston, SC, April 14–16, 2003.)

FIGURE 6.17 Full-scale trial embankment no. 2 at Son La RCC dam site. (From Water power and dam construction. The need for speed. Water power and dam construction. [Online] Available at http://www.waterpowermagazine.com/features/featurethe-need-for-speed/featurethe-need-for-speed-9.html [Accessed July 31, 2014].)

6.4.1 Preconsiderations

Good foundation and/or foundation treatment goes a long way in deciding the overall design and configuration of RCC. Design–specifications–equipment–scheduling–materials–construction–weather has to be integrally planned. As emphasized before, aggregate production, at least for dam construction, is an essential aspect of RCC. Optimal crusher design, reducing the number to fractions to practical minimum, schedule of aggregate production, carefully planned stockpiling, reduction of rehandling, and transportation are very important considerations in saving energy expenditures. Another vital point is optimal layout of aggregate crusher, aggregate cooling systems, and batching and mixing plants. This helps in making the flow of materials seamless and with just adequate energy consumption.

6.4.2 Batching and Mixing

There are two important points in placing voluminous RCC dams, viz. the speed and the volume of placement. Batching and mixing plants of both continuous and batch type are used and include conventional drum mixers, continuous pug mills, and twin-shaft mixers. Accuracy and consistency of batching are essential along with robustness of the system. From the point of view of mixing, rapid, thorough, and uniform blending with desired output are essential. For maintaining continuity of supply, sound, realistic, and adequate capacity planning of all the systems feeding materials while ensuring continuity is pivotal. Maintenance has to be routinely scheduled and performed during shift changes; any major breakdown could prove a costly affair, more in terms of time than in money. Standby batching and mixing plants are provided to cater to contingencies. Adequate moisture corrections are

FIGURE 6.18 RCC aggregate and concrete production facilities at Yeywa. (From Ortega, S F. Construction of Yeywa Hydropower Project in Myanmar—Focus on RCC technology. Freising, Germany, DTK, 14th German Dam Symposium & 7th ICOLD European Club Dam Symposium, Sept. 17–19, 2007.)

applied to balance for the aggregate moisture and losses due to ambient temperature and humidity. Systems of aggregate production and batching and mixing plants on typical RCC projects could be very elaborate and complex. Figure 6.18 shows an example [52].

6.4.3 Transportation

Transporting RCC from its mixing point to placement point requires a very detailed design. The placement operation commences from the bottom and gradually reaches the top with usually the volumes reducing as well. Chemical admixtures are usually used only for set retardation and not for workability retention. As such, the complete set of operation commencing from mixing through transportation, spreading, placement, and compaction should be completed in the least possible time, usually within 45 min. The transportation system could be a conveyor belt system or dump truck transportation or a combination of both. Adequate measures are taken to avoid moisture losses, segregation, and lift contamination during transportation. Figures 6.19 and 6.20 show examples [53,54].

6.4.4 Placing, Spreading, and Compaction

Placing of RCC can be achieved through swinging-type conveyor belt system or through dump trucks in the terminal section of concrete transportation. The direction of placement of RCC layers is decided by the dimensions of a dam. RCC is typically placed in thickness of 0.3 m in non-RCD type design philosophy, whereas multiple layers of either 0.15 or 0.3 m are placed in RCD philosophy (see Figure 6.21, Ref. [55]). Tracked dozers carefully maneuvering over fresh and uncompacted RCC

FIGURE 6.19 Conveyor line negotiating an at least 60° slope from the mixing plant at dam crest elevation to the bottom of the Gibe III Dam 245 m below. (From RCC Conveyors-USA, LLC. Portfolio–Gibe III dam. [Online] [Accessed July 31, 2014.] Available at http://www.rccc-usa.com/portfolio/GibeIIIDam.htm.)

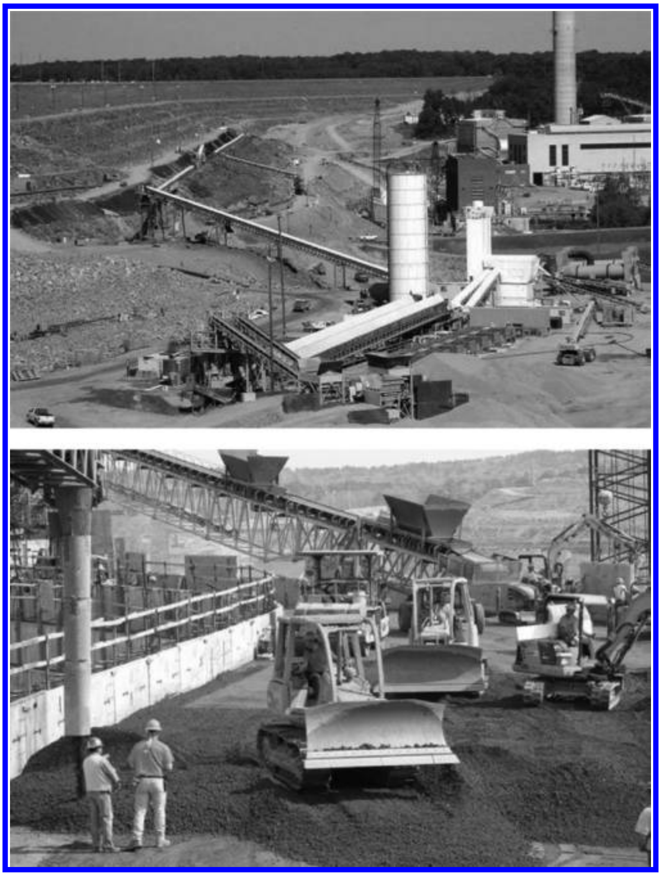

FIGURE 6.20 RCC-conveying system; terminal dumping using elephant trunk. (From Saluda dam remediation project. [Online] [Accessed July 31, 2014.] Available at http://www.falllinetesting.com/projects/saluda.php.)

are the most widely accepted pieces of equipment for spreading. Spreading time depends on the type of mixture and the allowable time between two successive lifts. Optimizing the layers and equipment and machinery fleet could save an appreciable amount of energy, time, and cost [3]. Recently, SLM of placement has been developed and successfully used for large dams with an advantage of time savings to the tune of 30%–50% [56].

Maneuverability, compactive force per unit of drum width, drum, size, vibration, frequency, amplitude, operating speed, availability, and required maintenance are all parameters usually considered in the selection of a roller. In addition, project size, RCC mixture workability, lift thickness, extent of consolidation due to dozer action, and space limitations will usually dictate roller selection. Single- or double-drum 10-ton rollers operating with higher frequency and lower amplitude are typically used for compaction. Heavier rollers are not that effective, whereas rubber-tired rollers have not been widely tested [3]. The roll–pass chart for calibrating the roller for specific RCC mixtures is developed during the full-scale trial. See Figures 6.22 and 6.23 [57,58].

FIGURE 6.21 RCD method of concrete placement. (From Gurdil, A F, Roller compacted concrete [RCC] dams in Turkey, Dushanbe, Tajikistan, s.n., Islamic Development Bank Group Annual Meeting, May 18–22, 2013.)

Typically, RCC operations are equipment intensive, and care has to be paid for keeping minimal manpower on the work front, specifically for safety reasons. A large dam construction can be busy, but small dam construction is busier and appears to be denser. See Figure 6.24 for a panoramic view of typical large RCC dam construction activities [59]. Joints between two lifts or lift joints are continuously kept moist

FIGURE 6.22 RCC placement on large dams. (From CHINCOLD. International Milestone project—Longtan dam. *CHINCOLD.* [Online] Jan 14, 2010. [Accessed July 31, 2014.] Available at http://www.chincold.org.cn/chincold/upload/files/20105119085144.pdf.)

FIGURE 6.23 Bedding mix and roller compaction. (From CHINCOLD. International Milestone project—Ralco dam. [Online] Jan 14, 2010. [Accessed July 31, 2014.] Available at http://www.chincold.org.cn/chincold/upload/files/20105419085451.pdf.)

in order to have a monolithic construction. This is done through time–temperature correlations of concrete layers.

6.4.5 Forms and Facings

The purpose of facings may be to control the seepage of water through the RCC lift joints, provide a surface that is resistant to freezing and thawing and durable against spillway flows, provide a means to construct a face steeper than the natural angle of repose of the RCC, and provide an aesthetically pleasing surface. Seepage may also be controlled by other methods [3]. A number of options are available for facings on both the downstream and upstream sides of the dams; the construction method, however, needs to be taken into account at the design stage.

The use of conventional concrete was the most common, until a method called GERCC was first used in the cofferdam for Puding Dam in China in 1994 and then for Jiangya Dam also in China. GERCC refers to the final product produced by adding grout to the surface of uncompacted RCC and, when combined with internal vibration, produces a homogeneous mass similar to that of conventional slump concrete. It may be described as in-place mixed concrete in an RCC dam. GERCC is a simple, cost-effective, fast, and durable system. Figure 6.25 shows the methodology.

6.4.6 Curing

Curing is an integral and continuous process in RCC construction. The compacted RCC layer is kept moist for proper preservation of moisture so that adequate bonding with the subsequent layer can be ensured. Curing during construction has been accomplished with modified trucks, handheld nozzles, automatic sprayers, or a combination thereof. Curing is usually done with fog nozzles capable of spraying fine mist that does not wash or erode the surface. Figure 6.26 shows an automatic spraying system used on a large dam.

FIGURE 6.24 Typical RCC construction site. (From CHINCOLD. International milestone project—Olinvehan dam. *CHINCOLD*. [Online] Jan 14, 2010. [Accessed July 31, 2014.] Available at http://www.chincold.org.cn/chincold/upload/files/20105519085522.pdf.)

FIGURE 6.25 Placement of GERCC.

FIGURE 6.26 Automatic spraying/curing method. (From CHINCOLD. International Milestone project—Longtan dam. *CHINCOLD*. [Online] Jan 14, 2010. [Accessed July 31, 2014.] Available at http://www.chincold.org.cn/chincold/upload/files/20105119085144.pdf.)

Contraction joints are typically provided depending on foundation restraint, temperature change, the time period over which it occurs, the tensile strain capacity of the concrete at the time in question, creep relaxation, the coefficient of thermal expansion of the concrete, and applied loads. Waterstops and drains are usually an integral part of a complete joint design [3]. Galleries and drainage arrangements are provided to ensure fulfilling the intended purposes, respectively.

6.5 RCCP-CONSTRUCTION METHOD

RCC for pavement applications is placed without forms and requires no additional finishing efforts or surface texturing, and because of the stiff nature of the fresh material, dowels or steel reinforcement is impossible to place. Because of its potential ability to accommodate a wide range of materials, this material and construction method offers engineering advantages in the form of reduced material cost, increased placement speed, reduced construction time, and lower maintenance costs. Considering the shrinking time scales of projects, especially in developed countries, this technology offers a time-efficient alternative to the conventional methods of pavement construction.

Mixed in various types of mixers (e.g., pug mill, continuous flow, rotating drum, horizontal twin shaft, pan, transit trucks), RCC requires vigorous mixing to ensure proper dispersion of the relatively small amount of water throughout the mixture. After mixing, RCC is then transported in covered dump trucks to the paving site within an acceptable time span (usually 45–60 min), with adequate compensation made for the moisture losses and thus loss of workability before concrete starts getting compacted.

RCC is paved on well-prepared, clean, and lightly moistened subgrade. The base material must provide sufficient stiffness to enable good compaction in the RCCP, must be sufficiently smooth to allow adequate smoothness of the RCCP surface, and should allow for adequate subsurface drainage under the RCCP. When used in concrete pavements as a base layer, a debonding sheet [60] or thin asphalt coat may also be used to create a positive separation layer between the RCC layer and conventional concrete. RCC is typically placed using heavy-duty asphalt pavers (regular, with extra screed, heavy tampers, heavy duty) or regular concrete pavers (with vibrators either lifted or removed) to the required thickness. The placement thickness is sufficient to allow for some reduction during compaction, so that the final compacted thickness is within design tolerances. A stringline is sometimes used to guide the paved screed to ensure that an adequate thickness and smoothness is achieved. One important aspect of the hauling cycle is maintaining a coordinated throughput. This is usually achieved by planning, matching, and regulating production and paving speeds and by arranging a suitable truck fleet for transportation while anticipating possible breakdowns and disruptions. Figures 6.27 through 6.30 illustrate subgrade preparation, production, construction, compaction, and curing operations [32,61–64].

Pavers used for RCCP are usually attached with extra screed to obtain better compaction during paving. Conventional concrete pavers can also be used either by lifting the needle vibrators or by removing them temporarily during RCC paving. With an assured and a continuous supply of concrete, the paving speed can be kept slightly higher than conventional concrete paving. The material is so stiff that one can stand on freshly paved RCC without damaging the pavement.

Immediately after placement, RCCP is compacted using vibratory drum rollers, sometimes followed immediately by pneumatic rollers to tighten the surface texture. The roll–pass chart is developed during the trial patch construction and is used for guiding the compaction effort during actual construction. The density is then monitored using a nuclear density gauge or any other suitable method of measuring in situ density. See Figure 6.30 for laying and compaction operations. Compaction (plain–vibratory–plain passes) is begun immediately after placement of the RCCP.

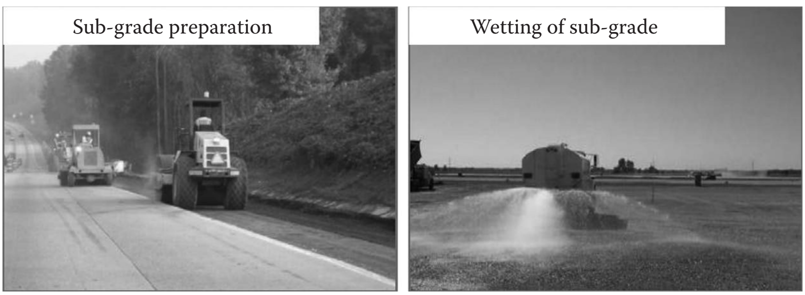

FIGURE 6.27 RCC subgrade preparation. (From Thompson, R R, *Roller Compacted Concrete Pavement: Design and Construction*, Columbus, OH, PCA and Kentucky Cement and Concrete Industry, 2002; Poole, B, Roller compacted concrete GDOT applications. In *Roller Compacted Concrete: Design and Construction*, Atlanta, GA, The Southeast Cement Association and PCA, 2008.)

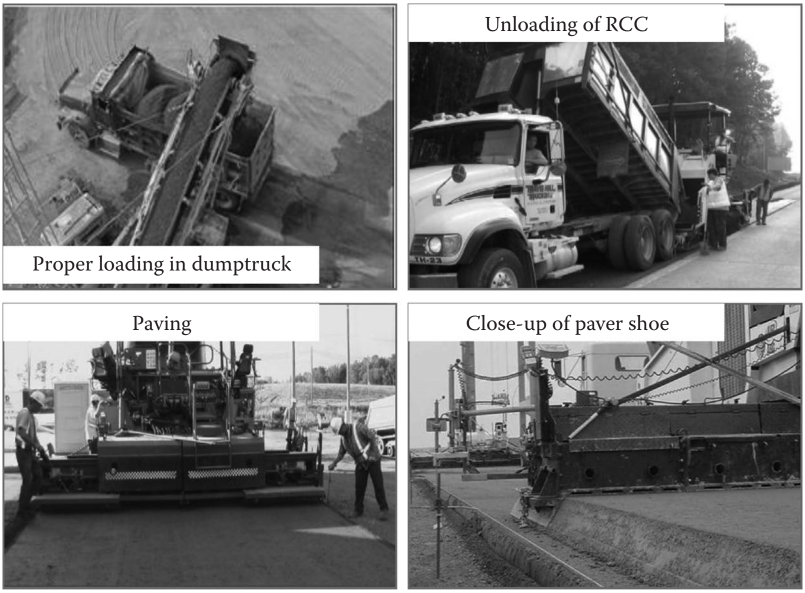

FIGURE 6.28 RCC loading, unloading, and paving. (From Poole, B, Roller compacted concrete GDOT applications. In *Roller Compacted Concrete: Design and Construction*, ed. Atlanta, GA, The Southeast Cement Association and PCA, 2008; Adaska, W, RE: RCC Section 7, a personal communication, Hazaree, C, 2009.)

The moisture content is monitored closely during placement and compaction, both from nuclear density gauge measurements and through visual observation of the pavement surface during compaction. Concrete on the drier side will tend to consume more fuel because it will demand greater number of passes and often might not achieve the specified degree of compaction. Likewise, mixtures on the wet side will lead to construction time losses because the roller will not be able to operate without forming a wavy surface or causing edge slump. Subsequent to compacting, the density is checked and verified before concluding the compaction for a given stretch of pavement. Any material that does not meet the density or smoothness requirements after compaction is either removed or repaired using diamond grinding (for smoothness) or retained at a reduced cost if the density reduction is minimal.

Saw cutting is usually started within the first 16–24 h. Depending upon the type of joint (transverse or longitudinal), the joint may be sealed with a suitable sealant. Sometimes, the pavement is left without any joint and allowed to crack in an uncontrolled way. Saw cutting may not be required when RCC is used as a pavement base or is going to be overlaid with asphalt or concrete. However, it is important to install saw cuts at regular intervals (with center-to-center distance much longer than conventional concrete pavements) to prevent unplanned cracks and associated damage during the lifetime of the pavement.

Moist curing is typically specified for the first 7 days. The RCCP surface should be kept continuously moist during the first 7 days; at no point or time after the paving

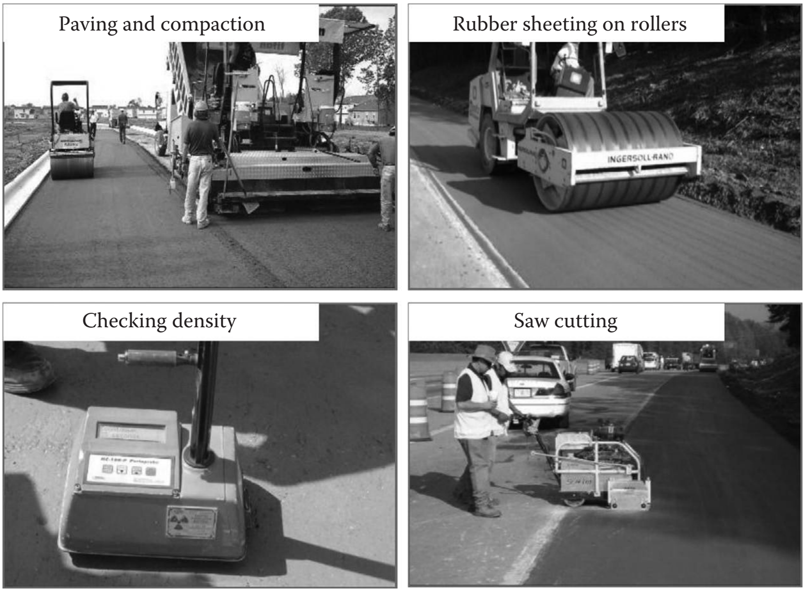

FIGURE 6.29 Compaction, density checking, and sawing. (From Poole, B, Roller compacted concrete GDOT applications. In *Roller Compacted Concrete: Design and Construction*, ed. Atlanta, GA, The Southeast Cement Association and PCA, 2008; Adaska, W, RE: RCC Section 7, a personal communication, Hazaree, C, 2009; McQueen, J. Project report—Houston port. In *Roller Compacted Concrete: Design and Construction*, Atlanta, GA, The Southeast Cement Association and PCA, 2008.)

FIGURE 6.30 RCC laying and compaction. (Courtesy of John Edwards.)

and compacting operations should the RCCP surface be allowed to dry. This can be achieved using water tankers fitted with sprayers or sprinklers or spreading plastic sheets on the wet surface of RCCP after the application of water spray. White pigmented membrane forming curing compounds may be used only if applied to a moist RCCP surface, in a uniform manner (no streaks or alternate rows of heavy and light applications), and of a thickness adequate enough to prevent moisture loss for at least 7 days. In some instances, an asphalt emulsion may be used for a curing compound, particularly if the RCCP will be covered with an asphalt concrete layer.

6.6 APPLICATIONS

6.6.1 Pavements

A very good aspect of RCC as a sustainable material and construction technique is its versatility of applications. This can also be seen in the adaptability of this material and construction practice to suit specific applications. Whether small or large scale or for regular or tough wear and tear, RCC can be used in a wide range of applications. The types of loads that RCCP can carry and the nature of traffic that it can handle vary widely. Depending on the type of application, the design methodology can differ. The following is a partial list of RCC applications:

- Airport apron areas (e.g., Denver International Airport)
- Composite construction consisting of RCC overlaid with a layer of asphalt
- Pavement bases (e.g., dry lean concrete base course beneath the wearing course in rigid pavements in India)
- Low-maintenance roads and parking areas (General Motors, Spring Hill, Tennessee)
- Industrial access roads surfaced with or without asphalt or concrete overlay (Tennessee DOT)
- Inlay rehabilitation (McMurray, Alberta, Canada), fast-track intersections (Calgary, Alberta, Canada), shoulder reconstruction (I285, Atlanta, Georgia), city streets (Lane Avenue, Columbus, Ohio), military hardstands (Ft. Drum, New York)

There are a number of applications in various areas that were mentioned in Sections 6.1 through 6.5. These are presented in this section to demonstrate that ports and heavy industrial facilities are large, open areas with few obstructions that may delay the construction process, making them ideal candidates for RCC. Pavements for ports and other heavy industrial facilities must be strong and durable because container-handling equipment can have wheel loads of 13.6–27.2 MT (30–60 kips) or more per tire (Figure 6.31). In applications where the desired thickness is greater than 10 in. (25.4 cm), two lifts are required [7].

FIGURE 6.31 Port facility in Houston, Texas, USA. (From Harrington, D et al., *Guide for Roller Compacted Concrete Pavements*, Ames, Iowa, CP Tech Center and PCA, 2010.)

FIGURE 6.32 Airport perimeter taxiway being paved with RCCP. (From Johnson, J, *RCC Pavement at Denver International Airport*, Skokie, IL, PCA, 2008.)

Airports commonly use RCCP for maintenance areas, parking lots, and snow storage areas. The pavement can withstand large loads, such as heavy snow plowing and heavy truck traffic during snow events. Moreover, RCC will not deteriorate under the saturated conditions caused by melting snow. Composite sections made up of an RCC base with a thin overlay of asphalt or unbonded concrete as depicted in Figure 6.32 have been used for runways, taxiways, and aprons [64]. Unsurfaced RCC pavements are not recommended for airplane traffic due to the possible dislodging of loose surface aggregate for the first 2 years [7].

Speed of construction, economy, and early opening to traffic are the key reasons to use RCC for streets and local roads (see Figure 6.33, Ref. [65]). In addition, using

FIGURE 6.33 RCC pavement or street used as a local road.

RCC for new residential developments provides a strong working platform during site work and construction. Surface treatments can be applied when the development nears completion. When traffic speeds are greater than 30 mph (48.3 km/h), surface smoothness is important. To achieve better surface smoothness, most projects use high-density pavers and/or diamond grinding. A thin asphalt surface course placed on top of the RCC is another option. In some cases, light traffic has been placed on the RCC pavement within 24 h of construction in order to accommodate nearby businesses [7].

6.6.2 Hydraulic Structures

RCC offers a wide range of economical and safe design alternatives to conventional concrete and embankment dams. The design of an RCC structure balances the use of available materials, the selection of structural features, and the proposed methods of construction. RCC dams can be constructed with straight or curved axes, with vertical or inclined upstream faces, and with downstream faces varying from vertical to any slope that is economically and structurally appropriate for a given site [3]. RCC structures can be built to serve a range of purposes and are often multipurpose.

The intended purposes include hydropower generation, irrigation, water supply, flood control, navigation, groundwater recharge, pollution control, fish farming, and recreational facilities. Depending on the intended purpose, material availability, topography, and geology, RCC structures could be designed. As of date, RCC structures built across the world are varying in dimensions, storage capacities, and RCC volume used in construction, the perplexity being that the dimensions and varied applications are continuously increasing. Apart from fresh applications, RCC is used for dam rehabilitation. Figures 6.34 through 6.38 show some examples [66–70].

FIGURE 6.34 Wolwedans arch-gravity dam in South Africa, primarily used for water supply. (From CHINCOLD. International milestone RCC project—Wolvedans dam. *CHINCOLD*. [Online] Jan 14, 2010. [Accessed July 31, 2014.] Available at http://www.chincold.org.cn/chincold/upload/files/20105219085213.pdf.)

FIGURE 6.35 Shimajigawa Dam, Japan; its main purpose is water supply. (From Dams in Japan. [Online] [Accessed July 31, 2014.] Available at http://damnet.or.jp/cgi-bin/binranA/enAll.cgi?db4=2086.)

FIGURE 6.36 Longton dam in China; used for hydropower, flood control, and water supply. (From Forbes, World's 39 Largest Electric Power Plants, [Online] [Accessed July 31, 2014.] Available at http://www.forbes.com/pictures/efee45jhji/no-9-longtan-dam/.)

Due to the versatility and adaptability, RCC is applied for foundation improvement, backfilling, cofferdams, embankments, slope protection works, new dam construction, rehabilitation of old dams, central core construction, spillways, increasing spillway capacities of earthfill dams, and grade control structures in rivers, and as seismic reinforcement for existing concrete dams [2].

FIGURE 6.37 Tarbela Dam, Pakistan; rehabilitation using RCC. (From Wikipedia, Tarbela dam, [Online] [Accessed July 31, 2014.] Available at http://en.wikipedia.org/wiki/Tarbela_Dam.)

FIGURE 6.38 General view of multipurpose Castanhao Dam, Brazil, used for flood control, irrigation, water supply, fish farming, and recreation. (From de Sousa Ponte, A T M et al., *The Multipurpose Castanhao Development on the Jaguaribe River*. Committee of Brazilian Dams, 2009.)

6.7 ASPECTS OF SUSTAINABILITY

RCCP is less costly than conventional Portland cement concrete (PCC) pavement. The USACE compared costs of RCC and conventional PCC pavements in 1995. The study analyzed 49 different USACE projects where RCC had been used for tank hardstands, tank trails, shipping yards, port facilities, maintenance yards, municipal streets, roads, parking areas, and other applications. Savings ranged from 14% to 58% [71]. Naik and Ramme [72] claim that initial cost savings of 15%–40% can be expected if RCC pavement is specified as a pavement alternative for projects requiring heavy wheel loading compared to conventional paving concrete.

Apart from the direct cost benefits that RCC offers in terms of cement savings and construction speed and constructability, the following features further enhance its sustainability rating:

- For a given cement factor, RCC will usually have higher strength than the conventional pavement concrete due to the dense aggregate packing achieved through proper proportioning of aggregates and compaction.
- Due to dense aggregate packing, the use of higher dosages of supplementary cementitious materials is possible.
- No dowel bars or tie rods are usually used in RCC. This in turn leads to comprehensive savings in materials, material cost, and associated processing during their manufacture and usage.
- No form works are required.
- No special finishing efforts are required. The pavement is finished during compaction itself. Texturing is usually not required.
- The use of asphalt pavers instead of concrete pavers reduces paving costs.
- The joint spacing can be increased, further reducing the cost of joint cutting and sealing.
- The pavement can be opened to traffic earlier than conventional concrete pavement.
- RCC as a material can accommodate more local materials than conventional concrete mixtures.
- Generally, the use of chemical admixtures is not required. Hence, the processing energies required for manufacturing chemical admixtures are saved.
- Since RCCP offers an integrated and comprehensive pavement alternative, it reduces the overall initial cost, thus saving the taxpayers' dollars. This offers a higher social sustainability rating to RCCP.

Harrington et al. [7] and Abdo and Shepherd [73] argue that RCC pavements provide sustainable pavement options because of the following qualities:

- Low embodied energy due to low production and maintenance energy use
- Reduced construction fuel demand compared to asphalt pavements due to thicker lifts
- Ability to use natural material, such as aggregate, in the most cost-efficient manner (by eliminating the need for substantial granular sub-base) while still providing high structural load-carrying capacity
- Ability to consume industrial by-products such as fly ash; ground, granulated blast furnace (GGBF) slag; and silica fume
- Ability to use more nonplastic fines, which reduces waste materials at quarries
- Longevity
- Low wheel-rolling resistance, which increases fuel economy
- Negative texture (needed for quiet pavements)
- Recyclability for use as future concrete or granular base
- High heat and light reflectance, with an RCC solar reflectance of greater than 29

It is also important not only to view materials from the sustainability perspective but also to look at the overall integration of sustainability principles in the design and construction of pavements. Considerations for such value-engineered, integrated paving solutions should be encouraged during the conceptualization and design phase of projects. Figures 6.39 and 6.40 highlight two examples showing sustainable savings achieved through such efforts.

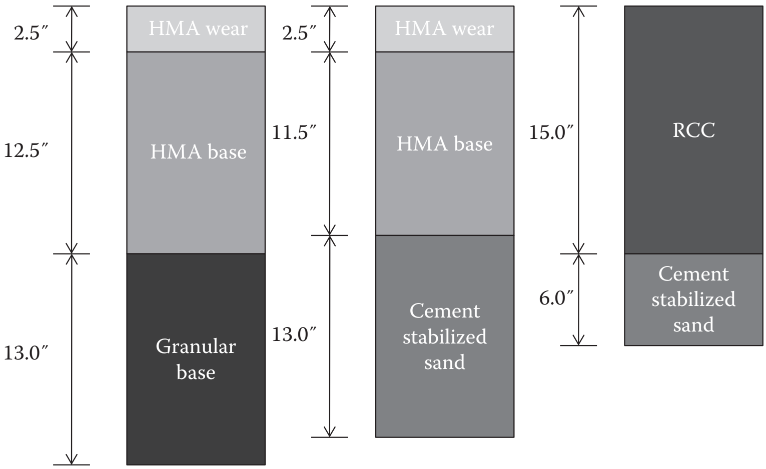

FIGURE 6.39 Sustainable alternative considered at Choctaw point terminal, Mobile, Alabama, USA. The key sustainability benefits include cost savings, longevity, reduced excavation, use of local materials, cooler pavement, and less damage to area roads. (From Abdo, F Y and Shepherd, D D, Innovative sustainable pavement solutions. NRMCA: NRMCA, Concrete Sustainability Conference, 2010.)

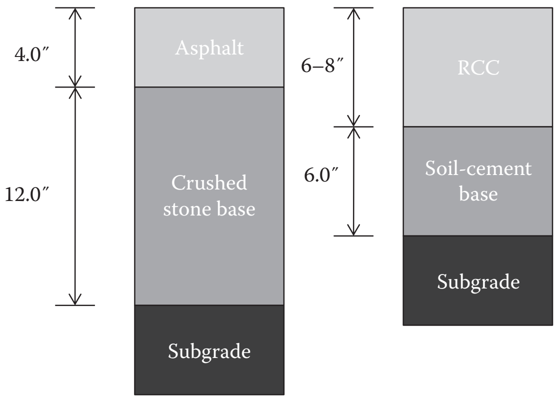

FIGURE 6.40 Options at BMW plant, Spartanburg, SC, USA. Significant sustainability benefits include reduced fuel cost, less processing energies, reduced excavation, and faster construction. (From Abdo, F Y and Shepherd, D D, Innovative sustainable pavement solutions. NRMCA: NRMCA, Concrete Sustainability Conference, 2010.)

RCCD sustainability is best achieved by first ensuring the following: (1) if the materials are a by-product; (2) properties/chemistry; (3) handling health hazard; (4) abundance; (5) logistics; and (6) economics. Notwithstanding the dam design principles being adopted, the development of RCC as a product for construction is usually decided on the prevalence of these six factors coming together. If it may also be included, territorial dominance leading to more complex diplomatic border disputes has, in some instances, been a major stumbling block for designers or engineers alike fulfilling the sustainable approach.

Next is the RCC concept itself, and there is no single definition. As has been discussed in previous notes, RCC from its inception is swirled around three or more indefinitive classifications, namely, low, medium, medium–high, and high paste. Any of this concept, should it be selected, has a direct impact on cost and time. For example, a high-paste RCC, though it requires that a prudent design process be followed, is incidentally far less complicated for construction hence dampening cost escalation and benefiting by faster return on investment.

6.8 PERFORMANCE OF RCC

Project development, design, engineering, and construction mark a very small time frame when compared to the actual performance of a structure for its intended purpose. Accelerated testing and durability testing can only provide a limited piece of information. The best test of a structure is the life over which it satisfactorily performs.

As stated earlier, for a given cement factor, RCC will usually offer better mechanical performance in terms of compressive and flexural strength. Not much research has been performed on the durability of RCC in general. However, the real-life performance of RCCP [25,43] over the past 20–30 years substantiates the fact that RCC can perform very well under severe climatic conditions and traffic loadings. Moreover, the F–T performance of RCC, even without the use of air-entraining admixtures, has been found to be satisfactory.

Because RCCD technology is relatively new, and documentation of structural performance is not readily available, the performance record for RCC dams is somewhat limited. However, the rapid acceptance of this approach to dam construction has resulted in many completed projects with a vast range of details, sizes, and locations. Performance involves design, construction, and operational performance. Completed RCCDs are performing their intended purpose quite well. Each type of RCC material and design tends to have advantages and disadvantages and performs better in some areas than in others [3].

6.9 GROWING APPLICATIONS: A HOPEFUL FUTURE

The applications of RCC are growing in the United States (Figure 6.41) [74]. Initially, RCC was used for military applications. However, in recent years, RCC applications have been widely accepted for private and industrial applications and include an array of applications, as listed in Section 6.8. In the last decade, the Portland Cement Association has invested substantial efforts in marketing RCC and educating contractors and consultants. Its efforts have led to widespread acceptance and

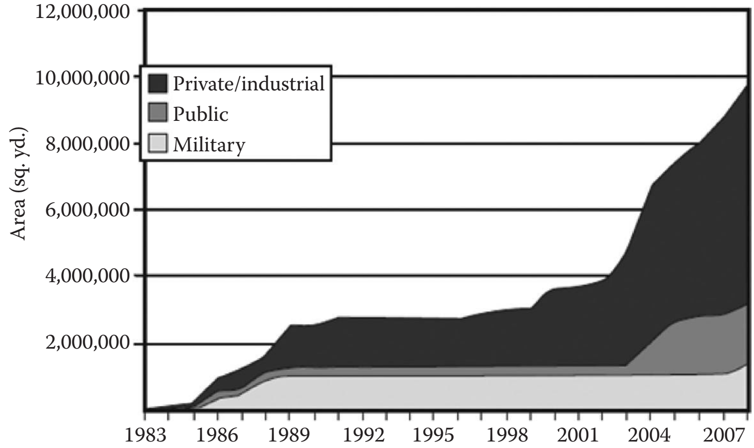

FIGURE 6.41 Growing applications of RCC in the United States. (From Pittman, D W and Anderton, G L, The use of roller-compacted concrete [RCC] pavements in the United States, Torino, Italy, s.n., Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control [MAIRE PAV 6], July 8–10, 2009.)

applications of RCC in the United States. The Cement Association of Canada has also invested substantial efforts in promoting the use of RCC.

The ambitious golden quadrilateral project [75] in India led to rapid construction of road infrastructure over the past 10–12 years. This work is continuing. With 65% of freight and 80% of passenger traffic carried by road infrastructure,

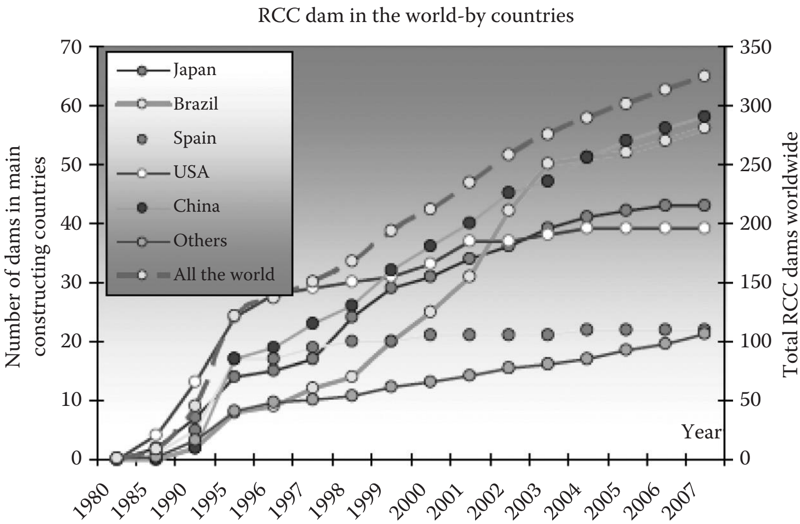

FIGURE 6.42 Growth of RCC dams by country. (From Gurdil, A F, Roller compacted concrete [RCC] dams in Turkey. Dushanbe, Tajikistan, s.n., Islamic Development Bank Group Annual Meeting, May 18–22, 2013.)

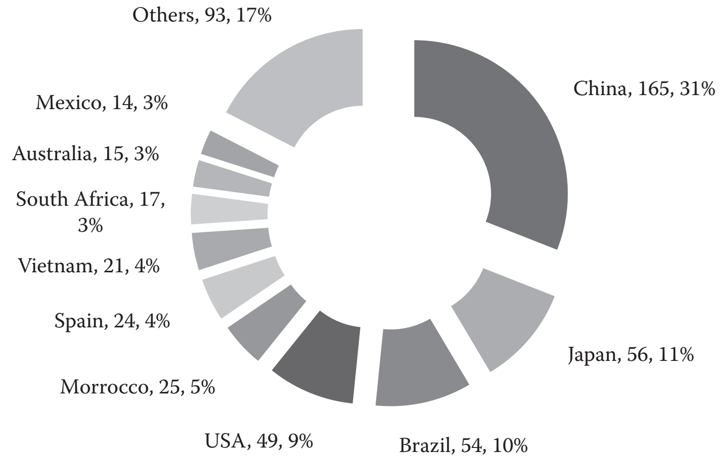

FIGURE 6.43 Demographics of RCC dams. (From Malcolm Dunstan & Associates. Dam database. *Malcolm Dunstan & Associates*. [Online] [Accessed July 31, 2014.] Available at http://www.rccdams.co.uk.)

there is a huge potential for further expansion. With several plans to construct road infrastructure underway, an integrated and sustainable choice of RCC as an alternative pavement material and construction method presents itself as an obvious choice.

RCC dams are also showing a continuously increasing trend. This trend is seen in all parts of the world—developed and developing countries alike, large or small dams, single-purpose or multipurpose, RCC technology has been serving all the causes well. Figure 6.42 shows the growth in RCC dams in countries that have embraced this technology and others, whereas Figure 6.43 shows a breakdown of the dams built in various countries.

6.10 CONCLUDING REMARKS

Depleting natural resources and environmental concerns are driving engineering efforts toward sustainability. The practice of compartmentalizing the process starting from conceptualization through to recycling is no longer workable. An integrated approach taking account of every aspect is required for a sustainable future. RCC material and construction technology offers such a consciously and sustainably engineered alternative solution.

RCC can be applied to two key infrastructure sectors that have a long-lasting impact on a nation's economy and sustainability. The rating systems for sustainability of concrete in general and RCC in particular need further evolution. The sustainability rating system for massive structures like dams actually needs to evolve from zero; construction without appreciating the sustainability footprint could prove to be catastrophically dangerous. The question is not whether a new material or a method is better than the older one in terms of sustainability; the question, however, is whether any method is sustainable or not. Additionally, the parameters defining sustainability also need to be evolved for each application.

Research and innovation are certainly required in the areas of improving RCCP design methods, pavement finishes, riding quality, materials, and durability. In regard to RCCD, further improvements in reducing the carbon footprint, optimizing equipment usage, and sustainability ratings are required.

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7 Pervious Concrete for Sustainable Development

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CONTENTS

7.1 INTRODUCTION

Concrete has always been known as a good, dense (solid), and durable construction material. In recent years, however, it has been found that even less solid ("pervious," as we call it) concrete can also be useful and durable and can contribute to sustainability in various ways. The purpose of this chapter is to introduce the reader to this new aspect of concrete and to the different benefits that can be derived and used to satisfy many criteria of sustainability applied earlier to other concretes. Although considerably more information is available, only a selected version is presented. The reader may pursue the topic further in his or her own way if it is of special interest.

7.2 WHAT IS PERVIOUS CONCRETE?

Pervious concrete (PC) is, by definition, concrete that has high porosity and allows water to drain freely—unlike dense, high-strength concrete. Its applications are therefore in situations where water from precipitation or other sources needs to be drained (see Figure 7.1). The high porosity is achieved by the absence or near absence of fine aggregates and a highly interconnected void content. PC thus may also be referred to as “no-fines concrete.” Sometimes, small amounts of fine aggregate are incorporated. It has been in the news recently for the role that it can play in creating a sustainable habitat. Globally, considerable research is being done on PC, which is usually used for concrete flatwork applications. PC helps reduce runoff from a site and allows for groundwater recharge (see Figure 7.2).

This environmentally friendly material is widely used for construction of low-loading intensity parking pavements, residential streets, greenhouses, areas with light traffic, sidewalks, and walkways in several developed countries today. It is also considered one of the most important low-impact development techniques that are available today to protect water quality. The material structure of any porous material influences its performance characteristics to a significant degree. PC is no exception. Identification of the critical pore structure features, their dependence on material parameters, and methods to characterize those features are important in ensuring that the performance of PCs be related to material design and that proper performance-based material design procedures are developed. Therefore, PC can be studied at a different level, based on its porosity; however, it alone is insufficient in providing a complete description of the material performance. For the interested

FIGURE 7.1 Demonstration of water draining in PC. (Courtesy of Green Builder.)

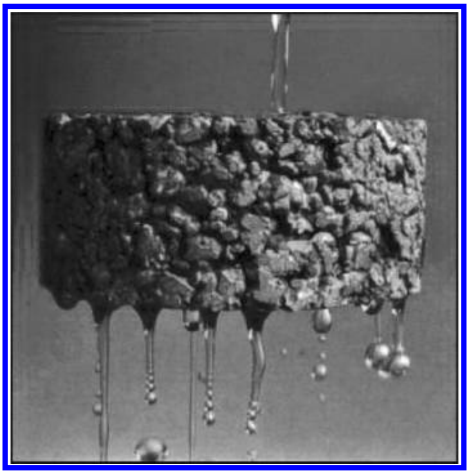

FIGURE 7.2 Typical PC. (Courtesy of Green Builder.)

readers, recent studies by Neithalath and others are presented in the Appendix* to distinguish them from the general discussion.

7.3 US ENVIRONMENTAL PROTECTION AGENCY AND PERVIOUS CONCRETE

The US Environmental Protection Agency has recognized PC as a best-management practice. PC has the capability to control storm-water overflow by allowing the water to percolate down to the earth, replenishing the earth's groundwater reserves in the process. In parking areas where spillage of coolants, engine oil, brake oil, etc., is an issue, this property of PC comes in handy because the material is capable of arresting the polluted water. This polluted water is then absorbed by the soil, where the natural elements take over and decompose the pollutants. Since PC reduces rainwater runoff, it also helps in reducing load on drainage systems. The replenishment of the groundwater table around pavement blocks made up of PC also can be utilized for planting and growing trees.

In addition to federal regulations, there has been a strong move in the United States toward sustainable development, which is development that meets the needs of the present generation without compromising the needs of future generations. In the United States, the US Green Building Council, through its Leadership in the Energy and Environmental Design (LEED) green building rating system, fosters sustainable construction of buildings. Projects are awarded silver, gold, or platinum certification depending on the number of credits they achieve. PC pavement qualifies for LEED credits and is therefore sought by owners desiring a high LEED certification.

* The Appendix was contributed by Dr. Narayanan Neithalath, PE, associate professor of civil engineering at Arizona State University; his efforts are gratefully acknowledged.

PC also naturally filters storm water and can reduce pollutant loads entering into streams, ponds, and rivers. It captures the first flush of rainfall (the first 30 min of rainfall, which will lead to a runoff with most pollutants) and allows that to percolate into the ground so that soil chemistry and biology can treat the polluted water. PC functions like a storm-water retention basin to allow the storm water to infiltrate the soil over a large area, thus facilitating recharge of precious groundwater supplies locally. All of these benefits lead to more effective land use. PC can also reduce the impact of development on trees. A PC pavement allows the transfer of both water and air to root systems, thus allowing trees to flourish even in highly developed areas.

7.4 CHARACTERISTICS AND DESIGN OF MATERIALS

PC (also known as porous, gap-graded, permeable, or enhanced porosity concrete) mainly consists of normal Portland cement, supplementary cementitious materials (SCMs) like fly ash and slag cement, coarse aggregate, and water. In normal concrete, the fine aggregates typically fill in the voids between the coarse aggregates. In PC, fine aggregate is nonexistent or present in very small amounts. Also, there is insufficient paste to fill the remaining voids, with the result that PC has a porosity anywhere from 15% to 35% but most frequently about 20%. Aggregate gradings used in PC are typically either single-sized coarse aggregate or grading between 3/4 and 3/8 in. (19 and 9.5 mm). All types of cementitious materials conforming to their American Society for Testing and Materials (ASTM) specifications have been used.

PC can be made without chemical admixtures, but it is not uncommon to find several types of chemical admixtures added to influence the performance in a favorable manner. PC uses the same materials as conventional concrete, with the exceptions that the fine aggregate typically is eliminated entirely, and the size distribution (grading) of the coarse aggregate is kept narrow, allowing for relatively little particle packing. This not only provides the useful hardened properties but also results in a mix that requires different considerations in mixing, placing, compaction, and curing. The mixture proportions are somewhat less forgiving than conventional concrete mixtures; tight controls on batching of all of the ingredients are necessary to provide the desired results. Often, local concrete producers will be able to best determine the mix proportions for locally available materials based on trial batching and experience.

7.5 CEMENTITIOUS MATERIALS

As in traditional concreting, Portland cements (ASTM C150, C1157) and blended cements (ASTM C595, C1157) may be used in PC. In addition, SCMs such as fly ash, natural pozzolans (ASTM C618), and ground-granulated blast furnace slag (ASTM C989) may be used. Testing materials beforehand through trial batching is strongly recommended so that properties that can be important to performance (setting time, rate of strength development, porosity, and permeability, among others) can be determined.

Water/cement ratios between 0.30 and 0.36 are used generally with proper inclusion of chemical admixtures, and those as high as 0.40 have been used successfully. The relation between strength and water/cement ratio is not clear for PC because, unlike conventional concrete, the total paste content is less than the void content between the aggregates. Therefore, making the paste stronger may not always lead to the increased overall strength. The void content has a stronger influence on compressive strength. Water content should be tightly controlled. The correct water content has been described as giving the mixture a wet, metallic sheen surface, without the paste flowing off the aggregate. A handful of PC formed into a ball will not crumble nor lose its void structure as the paste flows into the spaces between the aggregates, as shown in Figure 7.3. As a general rule, water that is drinkable is suitable for use in concrete, although recycled water from concrete production operations may be used as well if it meets the provisions of ASTM C94. If there is a question as to the suitability of a water source, trial batching with job materials is recommended.

Chemical admixtures are used in PC to obtain special properties, as in conventional concrete. Because of the low workability associated with PC, retarders or hydration-stabilizing admixtures are commonly used. Use of chemical admixtures should closely follow manufacturers' recommendations. Air-entraining admixtures can reduce freeze–thaw damage in PC and are used where freeze–thaw is a concern. ASTM C494 governs chemical admixtures, and ASTM C260 governs air-entraining

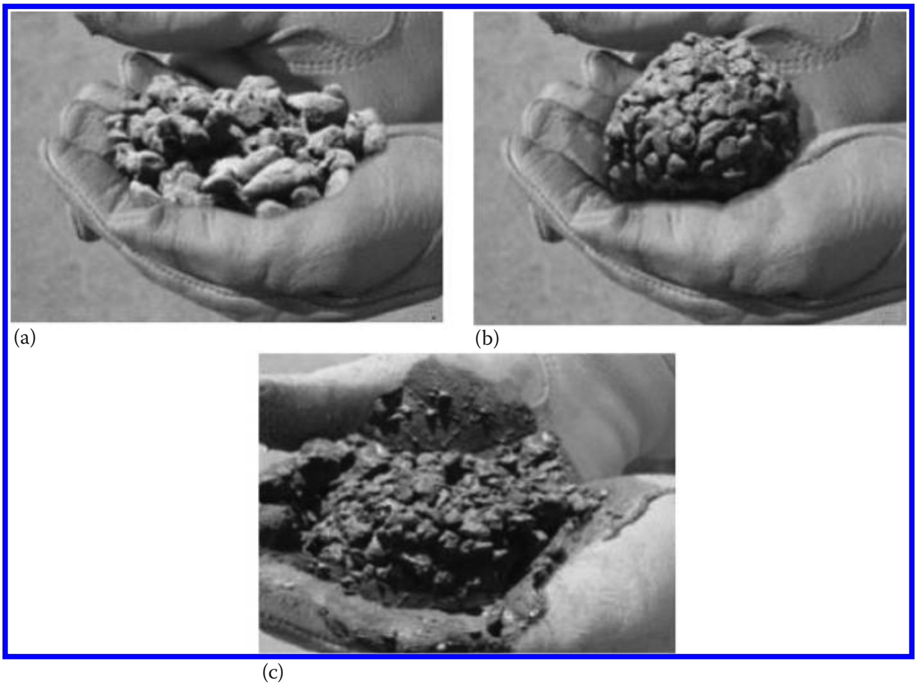

FIGURE 7.3 Samples of PC with different water contents, formed into a ball: (a) too little water, (b) proper amount of water, and (c) too much water.

admixtures. Proprietary admixture products that facilitate placement and protection of pervious pavements are also used.

The use of different materials and their design produces PC of different textures for different applications. Such applications make the user anticipate new uses for such concrete. Many of these are presented later in another section. Two mixes with different gradation of aggregates can be used for two different surface structures, making architectural applications of such concretes very feasible and new developments possible.

7.6 MIXTURE PROPORTIONS

Table 7.1 provides typical ranges of materials proportions in PC; ACI 522R-10 also provides a procedure for producing PC mixture proportions.

7.7 PROPERTIES OF PERVIOUS CONCRETE

The plastic PC mixture is generally stiff compared to traditional concrete. Slumps, when measured, are generally less than 3/4 in. (20 mm), although slumps as high as 2 in. (50 mm) have been used. However, slump of PC has no correlation with its workability and hence should not be specified as acceptance criteria. When placed and compacted, the aggregates are tightly adhered to one another and exhibit the characteristic open matrix that looks like popcorn. In-place densities on the order of 100–125 lb./ft.^{3} (1600–2000 kg/m^3) are common. PC mixtures can develop compressive strengths in the range of 500–4000 psi (3.5–28 MPa), which is suitable for a wide range of applications. Typical values are about 2500 psi (17 MPa).

TABLE 7.1
Typical Ranges of Material Proportions in Pervious Concrete

	Proportions (lb./yd.^{3})	Proportions (kg/m^3)
Cementitious materials	450–700	270–415
w/cm ratio[a]	0.27–0.34	
Aggregate/cement ratio[a]	4–4.5 to 1	
Fine/coarse aggregate ratio[b]	0–0.1	

Source: Available at http://www.torromeo.com/Services/Mix-Design-and-Materials.html.

Note: These proportions are given for information only. Successful mixture design will depend on properties of the particular materials used and must be tested in trial batches to establish proper proportions and determine expected behavior. Concrete producers may have mixture proportions for pervious concrete optimized for performance with local materials. In such instances, those proportions are preferable. Chemical admixtures, particularly retarders and hydration stabilizers, are also commonly used in dosages recommended by the manufacturer. Use of SCMs, such as fly ash and slag, is common as well.

[a] Higher ratios have been used, but significant reductions in strength and durability may result.

[b] Addition of fine aggregate will decrease the void content and increase strength.

The infiltration rate (permeability) of PC will vary with aggregate size and density of the mixture but will fall into the range of 2–18 gal/min/ft.^{2} (80–720 L/min/m^2). A moderate-porosity PC pavement system will typically have a permeability of 3.5 gal/min/ft.^{2} (143 L/min/m^2). Converting the units to inches per hour (millimeters per hour) yields 336 in./h (8534 mm/h). Perhaps nowhere in the world would one see such a heavy rainfall. In contrast, the steady-state infiltration rate of soil ranges from 1 in./h (25 mm/h) to 0.01 in./h (0.25 mm/h). This clearly suggests that, unless the PC is severely clogged up due to possibly poor maintenance, it is unlikely that the permeability of PC is the controlling factor in estimating runoff (if any) from a PC pavement. For a given rainfall intensity, the amount of runoff from a PC pavement system is controlled by the soil infiltration rate and the amount of water storage available in the PC and aggregate base (if any) under the PC.

Generally, for a given mixture, strength and permeability of PC are a function of the concrete density. The greater the amount of consolidation is, the higher the strength and the lower the permeability. Since it is not possible to duplicate the in-place consolidation levels in a PC pavement, one has to be cautious in interpreting the properties of PC specimens prepared in the laboratory. Such specimens may be adequate for quality assurance—namely, to ensure that the supplied concrete meets specifications. Core testing is recommended for knowing the in-place properties of the PC pavement. The relationship between the *water/cementitious material ratio* (w/cm) and compressive strength of conventional concrete is not significant. A *high w/cm* can result in the paste flowing from the aggregate and filling the void structure. A *low w/cm* can result in reduced adhesion between aggregate particles and placement problems. Flexural strength in PCs generally ranges between about 150 psi (1 MPa) and 550 psi (3.8 MPa).

Limited testing in freezing and thawing conditions indicates poor durability if the entire void structure is filled with water (NRMCA 2004). Numerous projects have been successfully executed and have lasted several winters in harsh northern climates in Indiana, Illinois, and Pennsylvania. This is possibly because PC is unlikely to remain saturated in the field. The freeze–thaw resistance of PC can be enhanced by the following measures:

- Use of fine aggregates to increase strength and slightly reduce voids content to about 15%–20%
- Use of air entrainment of the paste
- Use of a 6- to 18-in. (15- to 45-cm) aggregate base, particularly in areas of deep frost depths
- Use of a perforated PVC pipe in the aggregate base to capture all the water and let it drain away below the pavement

Abrasion and raveling could be a problem. Good curing practices and appropriate w/cm (not too low) are important to reduce raveling. Whereas severe raveling is unacceptable, some loose stones on a finished pavement are always expected. Use of snow ploughs could increase raveling. A plastic or rubber shield at the base of the plow blade may help prevent damage to the pavement.

7.8 DESIGN

Two factors determine the design thickness of pervious pavements: the hydraulic properties, such as permeability and volume of voids, and the mechanical properties, such as strength and stiffness.

ACI 522R-10 states that PC used in pavement systems must be designed to support the intended traffic load and contribute positively to the site-specific stormwater management strategy. The designer selects the appropriate material properties, the appropriate pavement thickness, and other characteristics needed to meet the hydrological requirements and anticipated traffic loads simultaneously. Separate analyses are required for both the hydraulic and the structural requirements, and the larger of the two values for pavement thickness will determine the final design thickness. Numerous applications have used a 5- to 6-in. (12- to 15-cm)-thick PC over an aggregate base generally of the same dimension. Field performance of these projects has shown that they are adequate to handle the traffic loads expected in parking lot-type applications (passenger cars), where the heaviest loads are generally from garbage trucks. If heavier loads and higher traffic are expected, then a thicker pavement (8–12 in. [20–30 cm]) is used. Another approach would be to try to use the structural design techniques outlined in the ACI 522R report, which could help optimize the pavement thickness.

Initial recommendations had been that PC should be used only in sandy soils with an infiltration rate greater than 0.5 in./h. However, a detailed hydrologic analysis for a specific example with soils with infiltration rate of 1, 0.5, 0.1, and 0.01 in./h has shown that the postconstruction runoff was lower in all four soils when compared to the preconstruction runoff. The draw-down time in all cases was acceptable, except for the soil with the lowest infiltration rate, and that, too, only when an aggregate base was used. The authors concluded that PC can be used in silty soils with a soil infiltration of only 0.1 in./h and that there is no need to limit its use arbitrarily only to sands. In soils with infiltration rates considerably less than 0.1 in./h, one way to reduce the draw-down time could be to use buried perforated pipes that can transfer the collected water elsewhere. If that is not feasible, the PC system could be placed without an aggregate base, and the resulting excess runoff over the PC (but still lower than if an impervious system had been used) could be handled using additional detention devices.

7.9 CONSTRUCTION

The success of PC pavements depends on the experience of the installer. As with any concrete pavement, proper *subgrade* preparation is important. The subgrade should be properly compacted to provide a uniform and stable surface. When pervious pavement is placed directly on sandy or gravelly soils, it is recommended to compact the subgrade to 92%–95% of the maximum density (ASTM D 1557). With silty or clayey soils, the level of compaction will depend on the specifics of the pavement design, and a layer of open graded stone may have to be placed over the soil. Engineering fabrics are often used to separate fine-grained soils from the stone layer. Care must be taken not to overcompact soil with swelling potential. The subgrade should be moistened prior to concrete placement to prevent the PC from setting and drying too quickly. Also, wheel ruts from construction traffic should be raked and recompacted.

The PC is sensitive to changes in *water content*, so field adjustment of the fresh mixture is usually necessary. The correct quantity of water in the concrete is critical. Too much water will cause segregation, and too little water will lead to balling in the mixer and very slow mixer unloading. Water content that is too low can also hinder adequate curing of the concrete and lead to a premature raveling surface failure. PC has little excess water in the mixture. Anytime the fresh material is allowed to sit exposed to the elements is time that it is losing water needed for curing. Drying of the cement paste can lead to a raveling failure of the pavement surface.

All *placement* operations and equipment should be designed and selected with this in mind and scheduled for rapid placement and immediate curing of the pavement. A PC pavement may be placed with either fixed forms or slipform pavers. The most common approach to placing PC is in forms on grade that have a riser strip on the top of each form such that the strike-off device is 3/8–1/2 in. (9–12 mm) above final pavement elevation. Strike-off may be by vibratory or manual screeds. After striking off the concrete, the riser strips are removed, and the concrete is compacted by a manually or mechanically operated roller that bridges the forms. Rolling consolidates the fresh concrete to provide a strong bond between the paste and the aggregate, creating a smoother riding surface. Excessive pressure when rolling should be avoided because it may cause the voids to collapse. Rolling should be performed immediately after strike-off. Since floating and troweling tend to close up the top surface of the voids, they are not carried out.

Jointing PC pavement follows the same rules as for concrete slabs on grade, with a few exceptions. With significantly less water in the fresh concrete, shrinkage of the hardened material is reduced significantly; thus, joint spacing may be wider. The rules of jointing geometry, however, remain the same. Joints in PC are tooled with a rolling jointing tool. This allows joints to be cut in a short time and allows curing to continue uninterrupted. Saw-cutting joints also are possible but are not preferred because slurry from sawing operations may block some of the voids, and excessive raveling of the joints often results. Removing covers to allow sawing can reduce the effectiveness of curing, and it is recommended that the surfaces be rewet before the covering is replaced. Some PC pavements are not jointed because random cracking is not viewed as a significant deficit in the aesthetics of the pavement (considering its texture) and has no significant effect on the structural integrity of the pavement.

Proper curing is essential to the structural integrity of a PC pavement. The open structure and relatively rough surface of PC expose more surface area of the cement paste to evaporation, making curing even more essential than in conventional concreting. Curing ensures sufficient hydration of the cement paste to provide the necessary strength in the pavement section to prevent raveling. Curing should begin within 20 min of final consolidation and continue through 7 days. Plastic sheeting is typically used to cure PC pavements.

Realizing the importance of the installer, the National Ready Mixed Concrete Association (NRMCA) developed and administers a PC contractor certification. The goal of the certification program is to ensure that knowledgeable contractors are selected to place the product and thereby minimize the chance for failure.

7.10 STANDARDS FOR TESTING AND MAINTENANCE

ASTM C1688 is a standard test method to determine the density and void content of freshly mixed PC. ASTM C1754 is a standard test method to determine the density and void content of hardened PC specimens, which can be cores or cylinders. It should be realized that the values obtained on a freshly mixed PC sample using standardized consolidation procedures can be significantly different from those measured on a pavement core. Various methods are used to place and consolidate PC in pavements. One should not expect equivalence of the measured densities by ASTM C1688 and that in C1754.

ASTM C1701 is a standard test method to calculate the infiltration rate of in-place PC (Figure 7.4). An infiltration ring is temporarily sealed to the surface of a pervious pavement. After prewetting the test location, a given mass of water is introduced into the ring, and the time for the water to infiltrate the pavement is recorded. The infiltration rate is calculated using the equations provided in the standard. Tests performed at the same location across a span of years may be used to detect a reduction of the infiltration rate of the PC, possibly by clogging, thereby identifying the need for remediation. A low-infiltration-rate reading on a new PC pavement suggests paste sealing during construction due to either improper mixture proportions or construction practices. This test should be conducted at several locations, and the average infiltration rate should be calculated.

ASTM C1747 is a standard test method to determine the potential resistance to raveling of PC by impact and abrasion. The test can be used to compare concrete mixtures.

ACI Committee 522.1 is a PC specification that requires the following test methods. Job site acceptance must be based on the density (unit weight) of fresh concrete measured according to ASTM C1688. An acceptable tolerance is ±5 lb./ft.^{3} (80 kg/m^3) of the design density. This ensures that the concrete that is supplied to the job site is the same as the concrete that was ordered for the project. Once the pavement has been constructed, cores are taken and tested for thickness and density. Density is determined according to ASTM C140. Slump and air content tests are not applicable to PC. ACI 522.1 also requires that each project include at least three PC installers or one craftsman who has received the PC contractor certification conducted by the NRMCA.

FIGURE 7.4 Infiltration rate testing of in-place PC. (From ASTM C1701-09.)

If the PC pavement is an element of the storm-water management plan, the designer should ensure that it is functioning properly through visual observation of its drainage characteristics prior to opening of the facility.

Maintenance of PC pavement consists primarily of prevention of clogging of the void structure. In preparing the site prior to construction, drainage of surrounding landscaping should be designed to prevent flow of materials onto pavement surfaces. The two commonly accepted maintenance methods are pressure washing and power vacuuming. Pressure washing forces the contaminants down through the pavement surface. This is effective, but care should be taken not to use too much pressure because this will damage the PC. Power vacuuming removes contaminants by extracting them from the pavement voids. The most effective scheme, however, is to combine the two techniques and power vacuum after pressure washing.

7.11 COMPARISON OF CONVENTIONAL AND PERVIOUS CONCRETE

Conventional and pervious concretes can be compared to indicate their usefulness in many applications:

Strengths	Less (due to lower density—15%–25% voids)
Durability	Similar (freeze–thaw separately discussed)
Appearance	Open graded
Aggregate	3/8-in. (10-mm) maximum size round pea gravel—typical (few fines)
Shrinkage (cracking)	Less (15–20 ft [4.5–6 m]) joint pattern)
W/C ratio	Lower
Set time	Faster (most cases, but modifiable)
Curing sensitivity	Much higher
Costs	Incremental in place is more than offset by reduction in storm-water handling systems

7.12 APPLICATIONS

Common applications for PC are parking lots, sidewalks, pathways, tennis courts, patios, slope stabilization, swimming pool decks, greenhouse floors, zoo areas, road shoulders, drains, noise barriers, friction courses for highway pavements, permeable bases under a normal concrete pavement, and low-volume roads. PC is generally not used solely for concrete pavements for high traffic and heavy wheel loads. Examples of a few applications of PC are shown in Figures 7.5 through 7.8.

The parking area of 70,000 ft.^{2} of PC at Linden High School in California provides an excellent annual groundwater recharge of 700,000 gal, or 2.2 ac-ft. (Figure 7.9). A similar example is the pervious parking area of the Vacaville Police Department building, which allowed the use of about 30,000 ft.^{2} of otherwise unusable space under the drip lines of landmark trees. The pervious area recharges the groundwater with about 350,000 gal (1.1 ac-ft.) every year (Youngs 2005).

(a) (b)

FIGURE 7.5 (a) Sidewalk and (b) low-volume pavements.

FIGURE 7.6 Parking lot with PC.

FIGURE 7.7 Driveway. (Courtesy of Wisconsin RMCA.)

FIGURE 7.8 PC in Miller Park, Fair Oaks, California, saved 23 mature olive trees. This parking area is designed to retain aesthetics while providing function and ADA compliance. (From Youngs, A., California–Nevada Cement Association presentation. Available at http://www.concreteresources.net; click "Pervious Concrete.")

FIGURE 7.9 Parking area in Linden High School, California. (From Youngs, A., California–Nevada Cement Association Presentation. Available at http://www.concreteresources.net; click "Pervious Concrete.")

7.13 SUSTAINABILITY

Another important factor leading to renewed interest in PC is an increasing emphasis on sustainable construction. Because of its benefits in controlling storm-water runoff and pollution prevention, PC has the potential to earn up to seven LEED credits:

- LEED credits SS-C6.1 and SS-C6.2: Storm-water design—quantity control
    - The intent of these credits is to limit disruption and pollution of natural water flows by managing storm-water runoff, increasing on-site infiltration, and eliminating contaminants.
- LEED credit SS-C7.1: Heat island effect—nonroof
    - The intent of this credit is to reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impact on microclimate and human and wildlife habitats.

- LEED credit WE C1.1: Water-efficient landscaping
  - The intent of this credit is to limit or eliminate the use of potable water or other natural surface or subsurface water resources available on or near the project site for landscape irrigation.
- LEED credits MR-C4.1 and MR-C4.2: Recycled content
  - The intent of these credits is to increase the demand for building products that have incorporated recycled content material, reducing the impacts resulting from the extraction of new material.
- LEED credits MR-C5.1 AND MR-C5.2: Regional materials
  - The intent of these credits is to increase demand for building products that are extracted and manufactured locally, thereby reducing the environmental impacts resulting from their transportation and supporting the local economy.

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APPENDIX: PORE STRUCTURE OF PERVIOUS CONCRETES AND ITS RELATIONSHIP TO PERFORMANCE

The material structure of any porous material influences its performance characteristics to a significant degree. PC has a complex pore structure (pore volume fraction and its distribution, sizes, shapes, and connectivity of pores), and its characterization is nontrivial. Identification of the critical pore structure features, their dependence on material parameters, and methods to characterize those features are important in ensuring that the performance of PCs could be related to material design and that proper performance-based material design procedures are developed.

Porosity is generally considered to be the most distinguishing feature of the pore structure of porous materials. In general, PCs are described based on porosity; however, this alone is insufficient in providing a complete description of the material performance. Porosity is a volumetric property of the material that does not depend on the configuration of the pores that contribute to porosity. To show this, 400 × 400 pixel^2 images of planar sections from PCs proportioned using three different aggregate sizes are shown in Figure A.1. The methodology for obtaining planar sections and image analysis has been detailed elsewhere (Sumanasooriya and Neithalath 2009; Neithalath et al. 2010a). All three parent PCs corresponding to these images have similar porosities between 18% and 22%, but their permeabilities were found to differ by more than 100%.

A.1 Pore Sizes and Methods for Representation

From Figure A.1, it can be seen that the pore structure of PCs is very irregular. Description of features of such media is fairly complex, and simple means of representation do not always suffice. Stereological or mathematical morphological theories are commonly used to describe the pore sizes in such random media (Sumanasooriya and Neithalath 2009).

Stereology deals with the three-dimensional interpretation of planar sections, and it can be used to evaluate the geometrical and statistical aspects of the chosen features of the material structure. Mathematical morphology quantitatively describes the geometrical

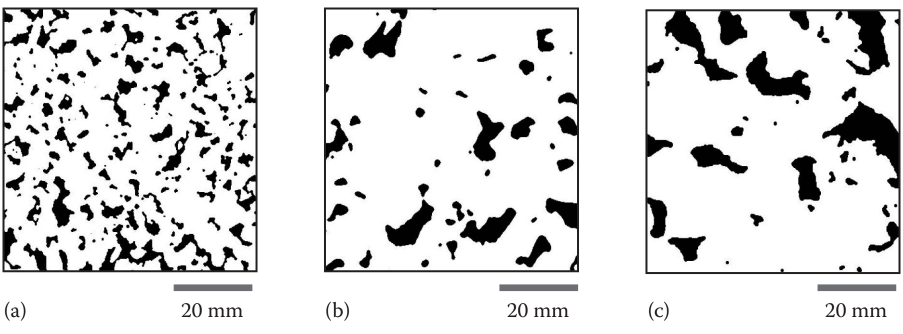

FIGURE A.1 Two-dimensional images of planar sections from PCs proportioned with (a) 2.36 mm, (b) 4.75 mm, and (c) 9.5 mm maximum size aggregates. The dark areas are the voids. (From Neithalath, N. et al., *Concrete International*, 32 (5): 35–40, 2010a.)

structure based on measuring the changes in an image when it is subjected to a particular transformation. The most common method to express pore size is the use of pore size histogram, which is a stereological measure. The area of each individual pore can be obtained from two-dimensional images (as shown in Figure A.1), and the equivalent diameters can be calculated by considering the pores as circles. Figure A.2 shows the pore size histogram and its cumulative frequency distribution of a typical PC mixture; this can be obtained from a simple image analysis procedure using any of the commercially available image analysis packages. From the cumulative frequency distribution, the effective pore size (d_{50}), which is defined as the pore size corresponding to 50% of the cumulative frequency distribution, can be obtained.

Advanced characterization methods such as the two-point correlation (TPC) function, which is a morphological method, can also be used to characterize a particular phase in a two-phase material. This methodology is more attractive since it provides extra information on the material structure, which is particularly useful in material modeling. This function contains information about the pore area fraction, the characteristic pore sizes, and the specific surface area of pores. The TPC function can be obtained by randomly throwing line segments of length l with a specific orientation into a two-dimensional image of a two-phase material and counting the fraction of times when both end points of the line lie in the phase of interest (Torquato 2002).

Figure A.3 shows a typical TPC function ($S_2(l)$) for a PC mixture. The value of the TPC function at $l = 0$ provides the porosity of the image. The correlation length (l_{TPC}), which is defined as the abscissa of the intersection point of the slope of the TPC function at $l = 0$ and the horizontal asymptote at which $l_{\text{TPC}} \to \infty$ provides an estimate of the pore diameter (d_{TPC}) as

$$d_{\text{TPC}} = \frac{l_{\text{TPC}}}{1 - \phi_A}$$

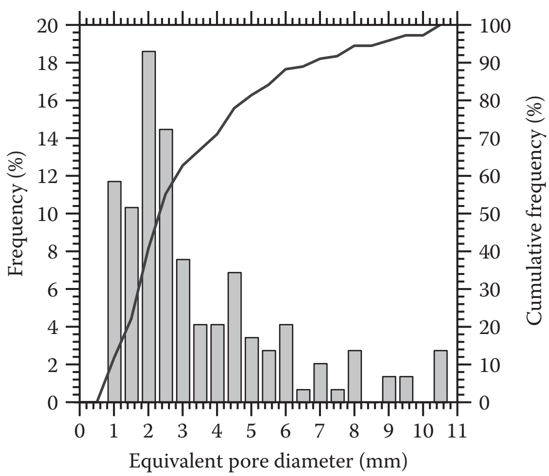

FIGURE A.2 Pore size distribution using area histogram and its cumulative frequency distribution curve.

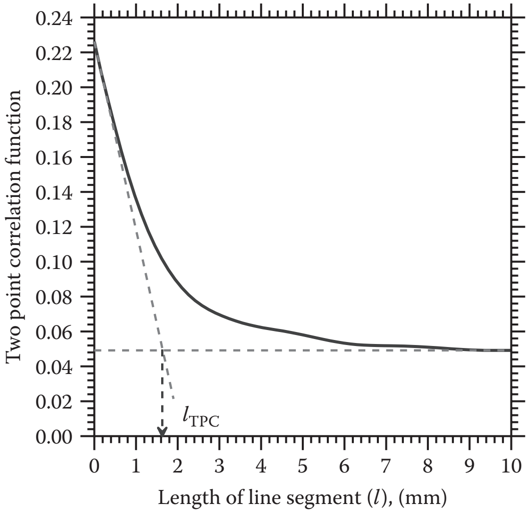

FIGURE A.3 TPC function for pore size determination for a typical PC specimen.

where ϕ_A is the pore area fraction of the image, which corresponds to the value of the TPC function at $l = 0$.

Another morphological method to determine the pore size is the granulometric distribution function, which is a morphological opening distribution function typically used to characterize the feature size distribution in two-dimensional images. The method consists of applying a morphological opening with structuring elements (SEs) of increasing size. In other words, if an SE of 1-mm radius is used to "open" the image, the resultant image will have only pores larger than 1 mm in radius. Figure A.4 shows an

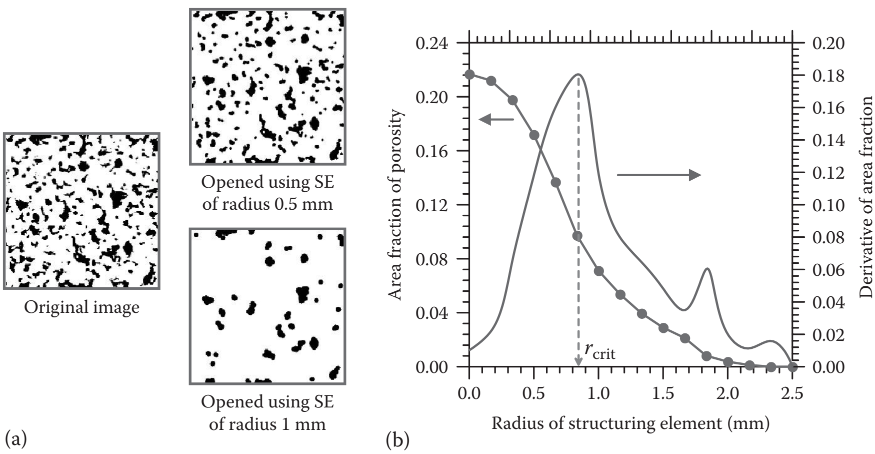

FIGURE A.4 (a) Original image and the resultant images after opening using SEs. (b) Critical pore radius from opening granulometry. (From Neithalath, N. et al., *Concrete International*, 32 (5): 35–40, 2010a; Neithalath, N. et al., *Materials Characterization*, 61 (8): 802–813, 2010b.)

original image and the images obtained by "opening" using SEs of two different sizes (Neithalath et al. 2010a,b). The size distribution is obtained by plotting the area fraction of the pore space remaining after opening by SEs of gradually increasing size, as shown in Figure A.4. The first derivative function of the area fraction of porosity is termed the granulometric density function, also shown in this figure. The radius of the circular SE corresponding to the local maximum in the derivative function relates to the critical pore radius (r_{crit}) of the material. The critical pore size is associated with the percolation threshold of porosity in the material and thus could be a useful parameter in permeability prediction (Sumanasooriya and Neithalath 2009; Neithalath et al. 2010b).

A.2 Specific Surface Area and Mean Free Spacing of Pores

A stereological method, such as using the perimeter length of the pores, or a morphological method, such as using the slope of the TPC at origin, can be used to determine the specific surface area (s_p), which is equal to the pore surface area (S_p) per unit volume. It has been rigorously shown (Torquato 2002) that the specific surface area can also be extracted from the TPC function, as shown in Figure A.3:

$$\underset{r \to 0}{Lt} \frac{\partial S_2(l)}{\partial r} = -\frac{S_p}{4V} = -\frac{s_p}{4}$$

where $S_2(l)$ is the TPC function.

The inverse of s_p is sometimes referred to as a characteristic length scale of the pores. For monosized, non-overlapping spherical pores of diameter d, it has been shown (Garboczi et al. 1999) that $1/s_p = d/6\phi$, where ϕ is the porosity. When empirical or semi-empirical relationships like Kozeny–Carman equations are used for permeability prediction of porous media, the specific surface area plays an important role (Neithalath et al. 2010a).

Dispersion of the phases in a two-phase random composite medium can be obtained using a stereological mean free spacing parameter. Mean free spacing (λ) is defined as the average value of uninterrupted surface-to-surface distances between all the neighboring pores. Lambda influences the mechanical properties of the porous material like strength and fracture behavior (Deo and Neithalath 2010) and can be related to the pore area fraction (ϕ_A) and the perimeter length of the pore features per unit area of the image (L_A) using the equation

$$\lambda = \frac{\pi(1-\phi_A)\phi_A}{L_A}$$

A.3 Connectivity of the Pore Structure

The effective electrical conductivity (σ_{eff}) of PCs can be determined using electrical techniques (Neithalath et al. 2006). The specimens sealed on the sides using latex sleeves are attached to a stainless-steel plate at the bottom with a piece of porous foam in between the specimen and the plate to ensure electrical contact. Sodium chloride of known concentration (say, 3%) and known conductivity σ_{pore} (4.4 S/m) is used to fill the pores in the PC specimen, and the top surface is sealed using another stainless-steel plate. The electrical measurements can be made at a single frequency or over a chosen frequency range. From the value of measured bulk resistance (recorded resistance if a single frequency is used or from a Nyquist* plot if a frequency range is used) (R_b), the effective conductivity (σ_{eff}) can be obtained as

$$\sigma_{eff} = \frac{l}{R_b A}$$

where A is the area of cross section of the specimens, and l is the length between the electrodes.

The effective electrical conductivity (σ_{eff}) of PC specimens can be stated as the product of the conductivity of the solution filling the pores in PC (σ_{pore}), the porosity (ϕ), and the pore connectivity factor (χ) as

$$\sigma_{eff} = \sigma_{pore}\phi\chi$$

A.4 Permeability and Its Relationship to Pore Structure

Contrary to conventional concretes, the larger and more connected voids in PC facilitate the measurements of porosity and permeability relatively easily. A simple falling head permeameter that can be used to determine the permeability of PC specimens that is commonly used is shown in Figure A.5.

Figure A.6 shows a compilation of porosity–permeability relationships from a few reported studies (Neithalath 2004; ACI 522R-06 2006; Low et al. 2008; Montes and Haselbach 2006; Wang et al. 2006). Though a general trend of increasing permeability with increasing porosity can be observed, it is seen from this figure that representing the permeability as a function of porosity alone is not adequate. In Section A.3, it was stated that porosity is not dependent on the constitution of the components (pores) that make it. Permeability prediction relationships for porous media such as the Kozeny–Carman equation or Katz–Thompson equation use other features of the pore structure, such as the characteristic length scale and pore connectivity, to estimate the transport parameters, such as permeability based on the pore structure (see Figure A.6).

The influence of pore structure features such as the measured porosity (ϕ), pore connectivity factor (χ), and critical pore sizes (d_{crit}) on the intrinsic permeability can be quantified through the use of established models. Previous studies (Katz and

* Plot of real versus imaginary impedance measurements. The meeting point of the bulk and electrode arcs is the bulk resistance.

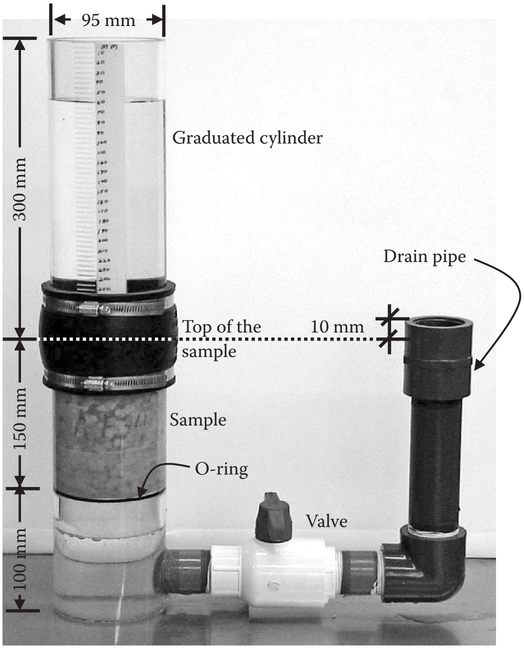

FIGURE A.5 Falling head permeability test setup for PC. (From Neithalath, N. et al., *Cement and Concrete Research*, 36:2074–2085, 2006.)

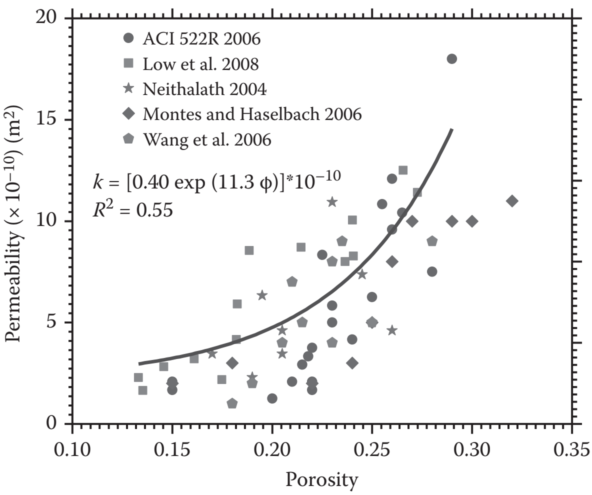

FIGURE A.6 Porosity–permeability relationships for several PC mixtures.

Thompson 1986; Banavar and Johnson 1987) have shown that, for a porous media, the intrinsic permeability can be stated as

$$k = C\frac{\sigma_{\text{eff}}}{\sigma_0}l_c^2$$

where C is a constant, and l_c is the characteristic length of the pores. The effective electrical conductivity (σ_{eff}) of PC specimens can be stated as the product of the conductivity of the solution filling the pores in PC (σ_{pore}), the porosity (ϕ), and the pore connectivity factor (χ) as

$$\sigma_{\text{eff}} = \sigma_{\text{pore}}\phi\chi$$

From the known value of σ_{pore} and the measured σ_{eff}, the value of $\phi\chi$, which is a pore structure parameter, can be extracted for all the PC mixtures.

Katz and Thompson (1986) used a proportionality constant, C, of 1/226 based on their study of porous rocks. For a variety of porous media, the characteristic length has been approximated by the hydraulic radius, a critical pore diameter, or a diffusion-limited trapping length (Martys and Garboczi 1992). The pore size obtained from granulometric distribution (d_{crit}) relates to the percolation threshold in PCs and is hence believed to be a realistic indicator of the characteristic length scale that controls permeability. The empirical constant (C = 1/226) can be related to the critical pore sizes.

The intrinsic permeability, k (units of square of the length), of porous media can also be described using the Kozeny–Carman equation as

$$k = \frac{\phi^3}{F_s\tau^2S_0^2(1-\phi)^2}$$

where ϕ is the porosity, F_s is the generalized factor to account for different pore shapes (two for circular tubes), τ is the tortuosity, and S_0 is the specific surface area of pores.

The tortuosity (τ) can be related to the pore connectivity factor (χ) as

$$\tau = \chi^{-1/2}$$

Using this expression and substituting $\sigma_{\text{eff}}/\sigma_{\text{pore}}$ for $\phi\chi$ helps rewrite the equation for k as

$$k \propto \left(\frac{\phi}{1-\phi}\right)^2\frac{\sigma_{\text{eff}}}{\sigma_{\text{pore}}}$$

This is similar to relationships that relate the intrinsic permeability to characteristic length of the pores (l_c) as

$$k \propto \left[\beta' \phi l_c^2 = \frac{\sigma_{eff}}{\sigma_{pore}} l_c^2 \right]$$

The right-hand portion of this equation is exactly the same as the Katz–Thompson equation.

The relative influence of the terms of the preceding equation (i.e., $\phi\chi$ and d_{crit}^2) on intrinsic permeability is shown using a contour plot of k as a function of both these parameters in Figure A.7. For a given $\phi\chi$, an increase in l_c^2 or d_{crit}^2 results in increased permeability. Therefore, increasing the pore sizes, which can be easily accomplished by using larger-sized aggregates, is an easy method to increase the permeability. At higher values of $\phi\chi$, the pore size does not seem to influence the permeability significantly for lower values of d_{crit}^2 as seen from contour lines that are essentially parallel to each other. However, at higher values of $\phi\chi$ and higher d_{crit}^2, there is a permeability increase. Higher values of $\phi\chi$ can be obtained by increasing the porosity or the connectivity factor. Very high porosities (typically more than 25%–30%) are generally undesirable from a viewpoint of mechanical properties.

Increasing the connectivity factors by careful material design procedures (including aggregate gradation, cement content, and compaction method) is perhaps the best possible means to obtain desirable transport properties. While designing for adequate porosity is straightforward, and porosity is easier to measure, material design of PC should also ensure adequate connectivity of the pore structure in order for the material to be efficient functionally.

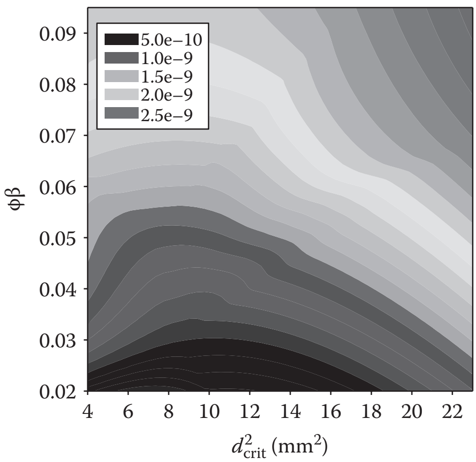

FIGURE A.7 Influence of d_{crit}^2 and $\phi\beta$ on intrinsic permeability of PCs. (From Deo, O., and N. Neithalath, *Materials Science and Engineering A*, 528 (1): 402–412, 2010.)

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8 Heat Island Effects

Pushpa Devanathan and Kolialum Devanathan

CONTENTS

8.1 INTRODUCTION

As urban areas develop, changes occur in their landscape. Buildings, roads, and other infrastructure replace open land and vegetation. Surfaces that were once permeable and moist become impermeable and dry. These changes cause urban regions to become warmer than their rural surroundings, forming "islands" of higher temperatures in the landscape.

Increased temperatures, especially in summer, may turn city centers into unwelcome hot areas, with direct effects on energy consumption for cooling buildings and morbidity and mortality risks for the population. These increased temperatures in the city center derive from the altered thermal balances in urban spaces, mainly due to the materials used and activities taking place in cities, which are far different from those in rural areas. The notably raised thermal capacity of urban materials, their low albedo, and their lack of porosity are the main characteristics of urban materials that are responsible for the formation of raised urban temperatures. The general lack of vegetation and the low albedo of urban surfaces are strong characteristics of the formation of the heat island effect.

Heat islands occur on the surface and in the atmosphere. On a hot, sunny summer day, the sun can heat dry, exposed urban surfaces, such as roofs and pavement, to temperatures hotter than air, while shaded or moist surfaces—often in more rural surroundings—remain close to air temperatures. Surface urban heat islands (UHIs) are typically present day and night but tend to be strongest during the day when the sun is shining (see Figure 8.1).

In contrast, atmospheric UHIs are often weak during the late morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban infrastructure. The annual mean air temperature of a city with 1 million people or more can be 1.8°F–5.4°F (1°C–3°C) warmer than its surroundings. On a clear, calm night, however, the temperature difference can be as much as 22°F (12°C).

Surface and atmospheric temperatures vary over different land-use areas. Surface temperatures vary more than air temperatures during the day, but they both are fairly similar at night. The dip and spike in surface temperatures over a pond show that

FIGURE 8.1 Schematic representation of UHI effect. (From http://earthobservatory.nasa.gov.)

water maintains a fairly constant temperature day and night due to its high heat capacity. Temperatures will fluctuate based on factors such as season, weather condition, sun intensity, and ground cover.

Regional climate change induced by rapid urbanization is responsible for and may result from changes in coupled human–ecological systems. Specifically, the distribution of urban vegetation may be an important intermediary between patterns of human settlement and regional climate spatial variability. The heat island sketch pictured in Figure 8.2 shows a city's heat island profile. It demonstrates how urban temperatures are typically lower at the urban–rural border than in dense downtown areas. The graph also shows how parks, open land, and bodies of water can create cooler areas.

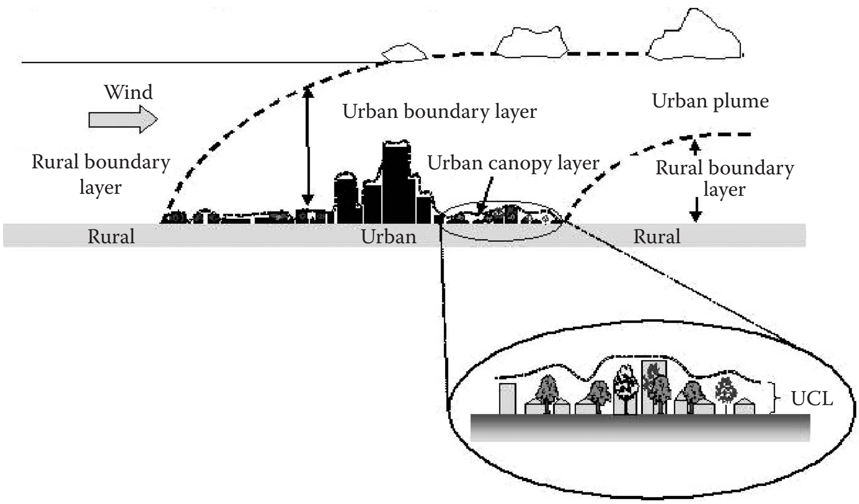

FIGURE 8.2 Schematic depictions of the main components of the urban atmosphere.

8.2 UHI EFFECT

According to the US Environmental Protection Agency (EPA), the UHI effect is "a measurable increase in ambient urban air temperatures resulting primarily from the replacement of vegetation with buildings, roads, and other heat absorbing infrastructure." The heat island effect can result in significant temperature differences between rural and urban areas.

8.2.1 What Is a UHI?

A UHI is a metropolitan area that is significantly warmer than its surroundings. As population centers grow in size from village to town to city, they tend to have a corresponding increase in average temperature. The term "heat island" refers to urban air and surface temperatures that are higher than nearby rural areas. Many US cities and suburbs have air temperatures up to 10°F (5.6°C) warmer than the surrounding natural land cover.

Unplanned and unsustainable urban development has led to severe environmental pressures. The green cover and groundwater resources have been forced to give way to rapidly developing urban centers. There is no controversy about cities generally tending to be warmer than their surroundings. Scientists compiling the historical temperature record are aware of the UHI effect.

Due to anthropogenic causes, climate change and variations are perceptible. Urbanization; industrialization; deforestation; increased numbers of concrete, glass, and metal-clad buildings; and changes in land-use patterns are some of the anthropogenic activities related to development that have had an effect on the climate.

From an ecological perspective, roofs, roads, and paving are perhaps the single most critical factor that sets cities apart from the countryside. The consequences of such a concentration of impervious surfaces, usually in the form of dark asphalt and roofing materials, extend to influencing the local climate and the local hydrology in varying degrees, depending upon the particulars of locational and ecological contexts. Taha (1997, p. 99) notes that "Northern Hemisphere urban areas annually have an average of 12% less solar radiation, 8% more clouds, 14% more rainfall, 10% more snowfall, and 15% more thunderstorms than their rural counterparts." Impervious surfaces are the hallmark of urbanization. Vitousek (1994) argues that land-use and land-cover (LULC) change, when taken together, is one of the three most significant global change processes that ecologists must take into account.

This concept has been recognized in publications since early in the Industrial Revolution. Oke (1995) simply defines a UHI as the "characteristic warmth" of a town or city. This warmth is a consequence of human modification of the surface and atmospheric properties that accompany urban development. This phenomenon is given its "island" designation due to the isotherm patterns of near-surface air temperature, which resembles the contours of an island rising above the cooler conditions that surround it.

This analogy is further illustrated in Figure 8.3, which shows a schematic representation of near-surface temperature for a large city, traversing from countryside to the city center. A typical "cliff" rises steeply near the rural/suburban boundary,

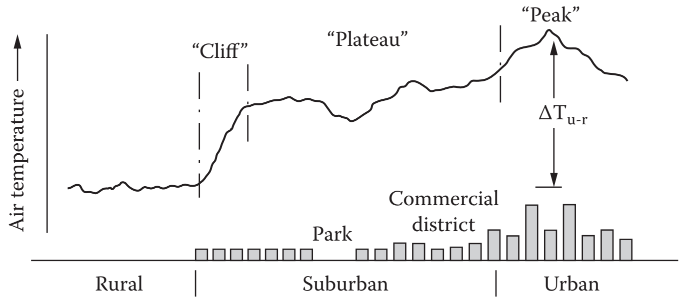

FIGURE 8.3 Generalized cross section of a typical UHI. (From Oke, T. R., *Journal of Royal Meteorological Society*, 108 (455): 1–24, 1982.)

followed by a "plateau" over much of the suburban area and then a "peak" over the city center (Oke 1987, 1995). The maximum difference in the urban peak temperature and the background rural temperature defines the UHI intensity. Over large metropolitan areas, there may be several plateaus and peaks in the surface temperature. Cooler patches coincide with open areas where vegetation or water is found.

The physical mechanisms through which the UHI effect is driven are well documented. Primary constituents of urban construction, such as asphalt, cement, and roofing tile, have a much greater heat capacity than forest vegetation and other natural features that have been increasingly displaced within metropolitan regions. As a result, urban structures absorb a large quantity of thermal energy during the daylight hours and slowly re-emit this stored heat during the late afternoon and into the night. The displacement of vegetation and soils further enhances heat retention by limiting the effectiveness of a natural cooling mechanism known as evapotranspiration.

Evapotranspiration is the process through which intercepted radiation is utilized by plants, soils, and water bodies to convert water to water vapor. The use of this energy in the evapotranspiration process reduces the amount of incoming solar and terrestrial radiation available to be absorbed by surface features and re-emitted as heat energy. The excess heat energy that is absorbed as a result of urban construction and deforestation is great enough to raise the average temperature of a city by several degrees over that of peripheral non-urbanized regions (Oke 1987).

Urban designs and forms that neglect local climatic conditions and lose the cooling effects of green areas tend to aggravate the heat island effect. Cities of poor countries in the tropics are particularly affected. Rapid urban growth, combined with the potent impacts of climate variability and climate change, will probably have severe consequences for environmental health in the tropics (causing, for example, heat stress and the buildup of tropospheric ozone), which can affect the urban economy (for example, yield of labor and economic activities) and social organization.

Heat islands may be measured as either surface or atmospheric phenomena. The temperature profile depicted in Figure 8.2 illustrates a much generalized distribution of near-surface (measured 1–2 m from the ground) air temperatures across varying intensities of urbanized land use. An elevation in near-surface air temperatures is known as the "canopy layer" heat island. Heat islands are also manifested through an elevation in the surface temperature of urban regions (the “surface” heat island; see Roth et al. 1989).

Surface-based measurements are also preferable for an analysis of land use and urban warming in that surface temperature may be measured through remote sensing (RS) techniques. In contrast to air temperature measurements that must be made through in situ observations on the ground, radiant emissions from surfaces can be measured remotely from radiometers mounted on aircraft or satellites. An advantage of RS techniques is that these methods facilitate the collection of a very large number of thermal observations.

An important theoretical premise is that increments in surface thermal emissions directly contribute to an elevation in atmospheric temperatures, with significant implications for air quality and human health. Evidence of a significant relationship between the surface and near-surface heat islands is provided from a number of studies. It is believed that surface-based measures provide a reliable basis for examining the interaction between urban design and elevations in both surface and near-surface air temperatures.

It is established that there is a recorded documented phenomenon called the UHI effect. There is a need to study the climatic changes in growing metropolitan cities around the world.

8.3 IMPACT OF URBAN WARMING

Heat island formation can influence air quality through a number of mechanisms. Most directly, elevated atmospheric temperatures are known to facilitate the series of chemical reactions through which ozone is formed (Cardelino and Chameides 1990). Toxic to humans at the ground level, ozone inflames lung tissue and aggravates a range of respiratory ailments, such as asthma. Urban warming can elevate ozone concentrations by increasing the rate at which volatile organic compounds (VOCs), a class of precursors to ozone, are emitted from vehicle engines and natural sources such as trees.

In recent years, the relationship between urban land use and environmental quality has received increased attention in both planning research and practice. Evidence provided from a range of studies on the interaction between land use and air quality has illustrated that moderate to high levels of density and an intermixing of compatible land uses can reduce vehicle travel and offset pollutant emissions. Urban intensification has the added benefit of reducing the acreage of rural land converted to suburban uses over time. In response to such findings, advocates of neotraditional design and “smart growth” management are re-embracing compact, pedestrian-scaled urban forms to achieve, in part, an environmental objective.

In addition to the potential for urban design to reduce air pollution through the facilitation of nonvehicle travel, there may be a more direct relationship between urban development patterns and air quality. Through a climatological phenomenon known as the *UHI effect*, large urbanized regions have been shown to alter their climates physically in the form of elevated temperatures relative to rural areas at their periphery.

Similar to the effects of global warming, the implications of “urban warming” for air quality and human health within affected regions can be substantial. While global warming forecasts predict a rise in temperature of 3.5°F–6°F (2°C–3.5°C) over the next century (IPCC 1995), large urbanized regions are already routinely measured to be 6°F–8°F (3.5°C–4.5°C) warmer than surrounding rural regions.

Increasing at a rate of 0.25°F–2°F (0.1°C–1.1°C) per decade, the heat island effect within urban cores of rapidly growing metropolitan regions may double within 50 years. In light of the roughly 2.9 billion new residents projected to arrive in urban regions between 1990 and 2025, there is a pressing need to ascertain the implications of urban warming for metropolitan regions and to identify potential strategies to counteract regional climate change.

UHIs are of interest primarily because they affect so many people. The impact of UHIs on the world's populace has the potential to be large and far reaching. As UHIs are characterized by increased temperature, they can potentially increase the magnitude and duration of heat waves within cities. Research has found that the mortality rate during a heat wave increases exponentially with the maximum temperature, an effect that is exacerbated by the UHI. Over the years, concern for the catastrophic effects on human health has prompted the development of strategies for reducing the UHI effect. These strategies have included reducing heat radiation and other emissions, expanding vegetated spaces, and, most recently, implementing cool roofs and green roofs.

8.4 FORMATION OF HEAT ISLANDS

Heat islands form as cities replace natural land cover with pavement, buildings, and other infrastructure. These changes contribute to higher urban temperatures in a number of ways. Waste heat from vehicles, factories, and air conditioners may add warmth to their surroundings, further exacerbating the heat island effect. Displacing trees and vegetation minimizes the natural cooling effects of shading and evaporation of water from soil and leaves (evapotranspiration). Tall buildings and narrow streets can heat air trapped between them and reduce air flow. In addition to these factors, heat island intensities depend on an area's weather and climate, proximity to water bodies, and topography. Measuring heat islands can help determine how these factors influence the heat island effect.

8.4.1 Indian Studies

8.4.1.1 Studies in Pune City*

Urbanization has a dynamic relationship with the physical environment. It has direct impact on the spatial structure of the city, which in turn results in the dramatic change of the overall immediate environment. Rapid urbanization often neglecting design issues related to urban climate is likely to increase levels of discomfort in cities. The cities are becoming a complex character consisting of different surface materials of low albedo and with lack of vegetative cover.

* Extract of paper presented on Study of Influence of Land Cover on Urban Heat Islands in Pune Using Remote Sensing by Pradnya Nesarikar-Patki and Pratima Raykar-Alange at the Second International Conference on Emerging Trends in Engineering. Dr. J. J. Magdum College of Engineering, Jaysingpur.

The objective of the study was to understand the role and influence of various land covers to achieve better microclimate in urban area. The method used was RS application IDRISI-Andes for prediction of temperature variations associated with different land cover types. To assess the thermal environment (UHI) of Pune for 1999 and 2006, the data were derived from Landsat images. There has been a 32.68% increase in the built-up area from 1999 to 2006 leading to a sharp decline of 10% area in agriculture and 21.91% area in barren land mostly attributing to the intense urbanization process. Vegetation has decreased by 10% from 1999 to 2006. There has been a 10°C–40°C rise in surface temperature in Pune from 1999 to 2006. Suburbs are heating up much faster than the inner city due to the construction boom. The study of UHI has been largely dependent on RS data and land surface temperature (LST) derived from the satellite data. IDRISI is an integrated geographic information system (GIS) and RS software for the analysis and display of digital geospatial information. Landsat can offer detailed mapping of Pune City's UHI.

The city has already engulfed a vast tract of the surrounding rural land by the dramatic sprawl and LULC since 1992. Out of the total area of 1337.58 km^2, there is change in land cover in 778.212 km^2 (58.18%) of the area, and in the remaining 559.36 km^2 (41.82%), there is no change in land cover. The growth poles are toward NW, S, and SE of the city indicating the intense urbanization process due to growth agents like setting up of IT corridors, industrial units, etc. Newly built-up areas in these regions consisted of the maximum number of small-scale industries, IT companies, multistoried buildings, and private houses that came up. The growth in the northern direction can be attributed to the airport at Lohegaon, encouraging other commercial and residential hubs. The southern part of the city is experiencing new residential and commercial layouts, and the south and west part of the city outgrowth corresponds to the development along with the Bangalore–Pune National Highway 4 and National Highway 9.

It was found that maximum temperatures were recorded over areas with a higher percentage of urbanization/building cover; the opposite was found for areas with a higher percentage of green cover. Of all the land use types studied, built-up areas showed the highest average temperatures.

The results showed that urbanization leads to LULC change and landscape pattern alteration, which responded obviously to the urbanization phases. The loss of agricultural land due to urban expansion cannot be totally halted but needs sustainable planning and management in protecting the loss of agricultural land. The data clearly show that the temperature rose by 2°C in the central parts of the city, while in the suburbs, it rose by 4°C–10°C.

8.4.1.2 Studies in Guwahati Metropolitan Area*

Changing urban landscape with high population growth and more demand for land is a major issue in Metropolitan Guwahati. The general pattern of urbanization in Guwahati is complex, diverse, and fragmented, which brings modification to natural land cover within the city. This complex urbanization process has altered the land

* This study was conducted by Monjit Borthakur and Bhrigu Kr. Nath and published in the *International Journal of Scientific and Research Publications*, Volume 2, Issue 11, November 2012.

surface characteristics within the city. Due to scarcity of vegetation, some hotspots on surrounding hillocks were identified, the surface temperature of which is as high as downtown.

Land cover provides the interaction between the biotic and abiotic components of the ecosystem, and thus changes to land cover also change biodiversity and evaporation and increase soil erosion and surface runoff. Urbanization, characterized by a typical land use type of impervious surface area, and engineering structures have caused a major change to the land cover. Thus, most of the areas of human disturbance such as towns and cities are characterized with closed isotherms indicating an area of the surface that is relatively warm. This process is well known as UHI.

The eco-sensitive zones (hills and wetlands) and the greenbelt of the city are continuously interspersed with the residential structures. The relation between urban land use and heat island effect may provide some insight into the development plans of the metropolis. If the relation between the land use and the UHI phenomenon can be properly articulated, the authorities may implement some countermeasures to minimize the effect of microclimatic change in their development plans.

The study was summarized as follows: During the last 20 years, the Guwahati Metropolitan Area has undergone phenomenal change in urban landscape that resulted in the loss of natural land cover. As a result, the surface temperature of the city has increased, and a prominent UHI is formed in and around the settlement areas. All these have severe environmental and health consequences. The land use regulation plan of Guwahati Metropolitan Development Authority's master plan can be a tool for sustainability of natural land cover. But the continuous intervention of human settlement to natural land covers in Guwahati Metropolitan Area has revealed the failure of land use zoning and regulatory action. The metropolitan development authorities should have strict regulation in the greenbelt and eco-sensitive areas of the city. Social forestry in the greenbelt areas, light-colored surfaces in residential units, plantation in the roof of buildings, and trees along the roads may be some countermeasures of the heat island effect in Guwahati Metropolitan Area. A solution to this problem is urgent in order to sustain the quality of urban life.

8.4.1.3 Studies in Delhi Metropolitan Area

By analyzing satellite images and field measurements, researchers have found that urbanization causes high surface temperatures, creating UHIs. UHIs can modify the climate, increasing the occurrence of heat waves in summer and hence increasing the risk of mortality in urban populations.

The LST is an important factor for climate change, and hence it is an important climate parameter in global climate models. Previous studies estimated LSTs in urban areas from satellite images of LULC, but they did not consider the effects of the atmosphere or the varying LULC patterns in urban areas. This limitation may introduce a temperature error of 4°C–7°C in models.

To reduce this error, the researchers estimated daytime and nighttime LSTs in Delhi from images captured by Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat satellites. In addition, to confirm the accuracy of the results obtained from the satellite images, they measured daytime and nighttime LSTs using an infrared thermometer.

The central and eastern districts of Delhi had the highest LSTs because they mainly consist of residential areas and networks of paved roads. Some parts of northwest Delhi had lower LSTs due to the presence of wasteland and fallow land. On the other hand, water bodies had the highest LSTs during the night.

Residential areas, industrial zones, and commercial hubs exhibited the highest LSTs. This implies that urban development does increase the LST through the replacement of natural vegetation with artificial surfaces such as stone, metal, and concrete.

The spatial layout of the LULC in Delhi has a great impact on the development of UHIs, which may affect the climate in the region. This highlights the need for urban planning to alleviate such effects.

Now, Indian government-backed research shows that both Delhi and India's biggest city, Mumbai, are becoming "UHIs," with significantly different climates to their surrounding rural areas. The Indian Institute of Technology (IIT)–Delhi has embarked on a major exercise to ascertain to what extent this phenomenon contributes to the temperature in the National Capital Territory (NCT). The congested city heart is much warmer than its green and open peripheries. This temperature difference can be felt more at night and when it rains, especially when winds are weak.

IIT scientists have already identified commercial areas such as Connaught Place, Sitaram Bazar, and Bhikaji Cama Place as the city's top three heat islands. Green pockets such as Hauz Khas district part, Sanjay Van, and the Buddha Jayanti Park are the cooler pockets. The experiment covered 30 spots after dividing the NCT into 16 major grid cells of 8 × 8 km in May 2008. The project, called Moderate Resolution Imaging Spectroradiometer, contributes to a validated, global, and interactive earth system model that helps predict environmental and climate change.

Preliminary findings from the Delhi-based The Energy and Resources Institute (TERI) show that temperatures in both cities have risen 2°C–3°C in only 15 years. The ongoing study, based on National Aeronautics and Space Administration (NASA) satellite readings, also shows the cities to be 5°C–7°C warmer than in the surrounding rural areas on summer nights.

The phenomenon of UHIs is recognized as a direct consequence of urbanization. Like many other cities in developing countries, Delhi and Mumbai have more than doubled in size and population in the past 25 years as rural migrants have flooded in.

However, artificial urban surfaces such as concrete and asphalt act as a giant reservoir of heat, absorbing it in the day and releasing it at night. Pollutants from nose-to-tail traffic add to the heat and, in a vicious cycle, people turn to air conditioning, which pumps out yet more heat and pollutants, so increasing climate-changing emissions, which lead to warmer global conditions.

Incessant urbanization increases LSTs, and, over time, the city ends up as an island of heat. Delhi, Mumbai, and their residents have been facing this onslaught of heat for 20 years. This could lead to unprecedented repercussions such as heat waves, health impacts, human discomfort, and increased mortality among the elderly. The UHI effects are directly related to and worsened by climate change, where it is expected that an increase in the average temperature will have a stronger effect on the health of people living in cities.

It is recommended that the best way to make cities livable is to contain sprawl and increase the amount of vegetation. Building water-retentive pavements and installing reflective roofs can be adopted to combat surface heat. The need of the hour is to control urban sprawl and put in place stringent policies for sustainable urbanization. Large cities are being found to have surprising impacts on surrounding areas. The extra heat they can generate can induce showers and even thunderstorms and increases downwind of cities.

8.4.1.4 Studies in Bangalore Metropolitan Area*

Taking information and methods collected from studies into consideration, this study has attempted to quantify the removal of particulate matter by trees at four locations in Bangalore City. Trees, shrubs, and green cover in general are hereafter referred to collectively as "trees." Locations are chosen on a comparative basis, with values taken from two sites (as a set) chosen based on the following:

- Both sites to be compared had similar traffic volumes.
- The sites had similar morphological/geological characteristics.
- Satellite images were studied to ensure that the sites did not possess other features that may affect ambient temperatures and particulate levels.

After studying recent maps of the area and its geological characteristics, the difference in temperature between the Circle site at the termination of Nrupatunga road and Nrupatunga road site is hypothesized to be a factor of the difference in tree cover, more specifically, of the shading of the road provided by trees at the Nrupatunga road site.

The difference in road temperatures (of 9.2°C) between the Bellandhur gate site and the Sarjapur Road site is hypothesized to be entirely a factor of the additional tree cover present at the Sarjapur road site and the complete lack of trees, hence tree shade, at the Bellandhur gate site.

Significant decreases in ambient air and road temperatures were seen in areas with tree cover over areas lacking tree cover. This reduction is significant both to human health and the economy in terms of reducing the severely damaging effects of the UHI effect. Taking the results of this study into consideration, it seems clear that additional studies on the role of pollution mitigation by trees should be carried out to prove the point.

While researchers are still studying the extent to which heat islands affect temperature related mortality in a city, implementing heat island reduction strategies like installing cool roofs, using cool paving, planting shade trees, and vegetation can minimize vulnerability among sensitive population.

The study undertaken by Minni Sastry, Mili Majumder, Pradeep Kumar, and D E V S Kiran Kumar (Sustainable Urban Development: Minimizing Urban Heat Island Effect and Imperviousness Factor) presents some evidence indicating the existence of heat islands in Bangalore City. The impact of vegetation and water bodies on the

* SECON's Study: Urban Trees in Bangalore City: Role of Trees in Mitigating Air Pollution and the Heat Island Effect (2006–2007).

urban microclimate was also studied. Field experiments carried out for various UHI mitigation options helped to derive significant conclusions. The measured data were validated with an ENVI-met software model, using parametric analyses for mitigation strategies.

Conclusions from this study reveal that it is evident that though the air temperatures during daytime are lower due to less solar exposure, night temperatures increase drastically in densely developed Commercial Street. About 0.8°C–2°C higher mean air temperature was observed during the measured period, which confirms the presence of UHI. Narrow streets with respect to lower solar exposure are important in case of pedestrian movement. Hence, the roof is the more critical area to change its surface type and reduce the air temperatures.

At the Indian Institute of Science (IISC) site, higher night temperatures (about 1.5°C) were observed where all mature trees are present. This leads to the conclusion that small leaf trees are more effective compared to big leaf trees in this respect.

Maintenance-free reflective white coating applications have insulation property due to the nanoparticles highlighted in this study. These coatings do not lose their performance when cleaned periodically. These are helpful in reducing the maintenance and operational energy costs. Infiltration increases, and thus potential increase in ground water table may be realized by the use of grid pavers.

The study conducted by Dr. T. V. Ramachandra and Uttam Kumar (2010) of the Energy and Wetlands Research Group, Centre for Ecological Sciences, IISC, Bangalore, reveals further data and reinforces the presence of heat island over the metropolitan area of Bangalore.

Urbanization and the consequent loss of lakes have led to the decrease in catchment yield, water storage capacity, wetland area, the number of migratory birds, flora and fauna diversity, and ground water table. As land is converted, it loses its ability to absorb rainfall. Also, increased urbanization has resulted in higher population densities in certain wards, which incidentally have higher LST due to a high level of anthropogenic activities.

The growth poles are toward N, NE, S, and SE of the city indicating the intense urbanization process due to growth agents like setting up of IT corridors, industrial units, etc. Newly built-up areas in these regions consisted of the maximum number of small-scale industries, IT companies, multistoried buildings, and private houses that came up in the last decade. The growth in the northern direction can be attributed to the new international airport, encouraging other commercial and residential hubs. The southern part of the city is experiencing new residential and commercial layouts, and the northwestern part of the city outgrowth corresponds to the Peenya industrial belt along with the Bangalore–Pune National Highway 4.

It is clear that urban areas that include commercial, industrial, and residential land exhibited the highest temperature followed by open ground. The lowest temperature was observed in water bodies across all years and vegetation.

There has been a 632% increase in the built-up area from 1973 to 2009 leading to a sharp decline of 79% area in water bodies in Greater Bangalore mostly attributing to the intense urbanization process. The rapid development of urban sprawl has many potentially detrimental effects including the loss of valuable agricultural and eco-sensitive (e.g., wetlands, forests) lands, enhanced energy consumption, and greenhouse gas emissions from increasing private vehicle use (Ramachandra and Shwetmala 2009). Vegetation has decreased by 32% from 1973 to 1992, by 38% from 1992 to 2002, and by 63% from 2002 to 2009. Disappearance of water bodies or sharp decline in the number of water bodies in Bangalore is mainly due to intense urbanization and urban sprawl. Many lakes (54%) were unauthorized encroached for illegal buildings. Field survey (during July–August 2007) shows that nearly 66% of lakes are sewage fed, 14% are surrounded by slums, and 72% showed loss of catchment area.

Also, lake catchments were used as dumping yards for either municipal solid waste or building debris. The surrounding of these lakes has illegal constructions of buildings, and most of the time, slum dwellers occupy the adjoining areas. At many sites, water is used for washing and household activities, and even fishing was observed at one of these sites. Multistoried buildings have been constructed on some lake beds that have totally intervened in the natural catchment flow leading to sharp decline and deteriorating quality of water bodies. This is correlated with the increase in the built-up area from the concentrated growth model focusing on Bangalore, adopted by the state machinery, affecting severely open spaces and in particular water bodies. The city corporations have restored some of the lakes together with the concerned authorities in recent times.

8.5 EXISTING CAUSES OF UHI EFFECT

8.5.1 Existing Parameters Known to Cause a UHI Effect

The following parameters can cause a UHI effect (see Figure 8.4):

- Increase in the built form and the geometric effect of built form
- Increase in traffic and pollution levels—air quality
- Loss of tree cover
- Topping of roads using asphalt
- Greenhouse gas emissions—ozone depletion
- Population increase—demographic changes
- Unplanned and unsustainable urban development
- Use of dark materials and surfaces that do not reflect heat
- Roofing materials
- Paving materials
- Increase in infrastructure activities of cities
- Climate and topography

8.5.2 Increase in the Built Form and Its Geometric Effect

Urban areas generate more heat than other areas because of population, manufacturing, transportation, and other causes. Urban areas also are heat traps, and this compounds the problem. The EPA discusses one of the reasons when it says that "heat islands form as vegetation is replaced by asphalt and concrete for roads, buildings,

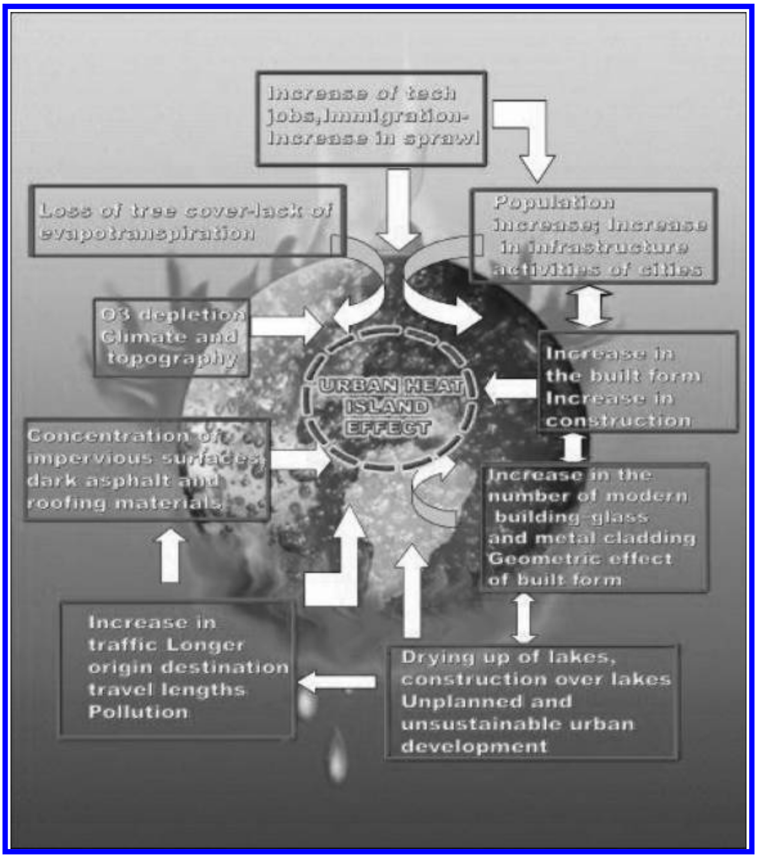

FIGURE 8.4 Pictorial depiction of parameters causing heat island effect. (Courtesy of the authors.)

and other structures necessary to accommodate growing populations. These surfaces absorb—rather than reflect—the sun's heat, causing surface temperatures and overall ambient temperatures to rise."

Albedo, or solar reflectance, is a measure of a material's ability to reflect sunlight on a scale of 0 to 1 (see Figure 8.5). An albedo value of 0.0 indicates that the surface absorbs all solar radiation, and a 1.0 albedo value represents total reflectivity. With a remarkable increase in the built form, the albedo of concrete and steel, modern construction materials add to the number of surfaces reflecting the heat. Less absorption takes place, which increases the temperature.

The UHI phenomenon was first discovered in the early 1800s in London. The focus of research now is on the driving forces, magnitude, and overall extent of the effect. As the heat in a city builds, it causes hot air to rise. Colder air from outside the city then rushes into the vacuum, creating winds. The warmer rising air begins to cool, forming convective clouds that typically produce localized thunderstorms and rain (see Figure 8.6). "Heat hunters" Dr. Dale Quattrochi and Dr. Jeff Luvall study

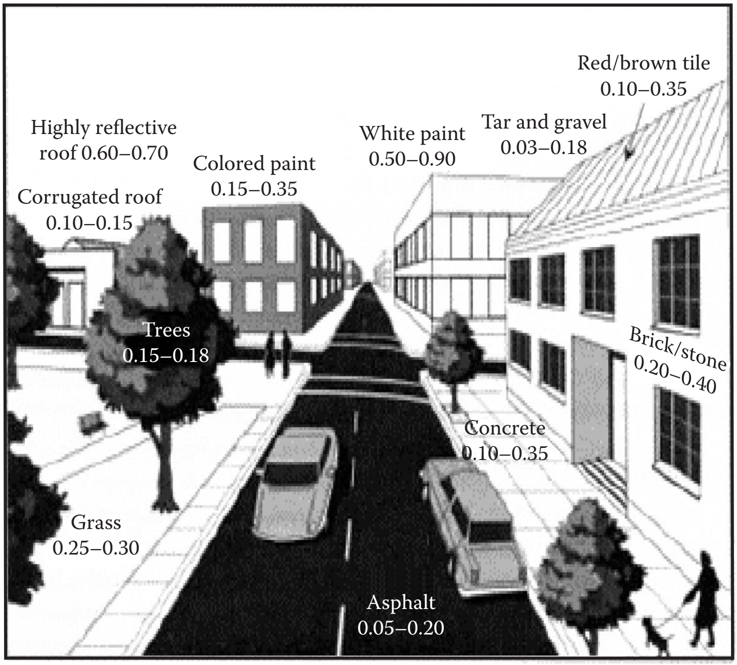

FIGURE 8.5 Albedo of various materials. (From http://www.heatislandeffect/EPA.gov.)

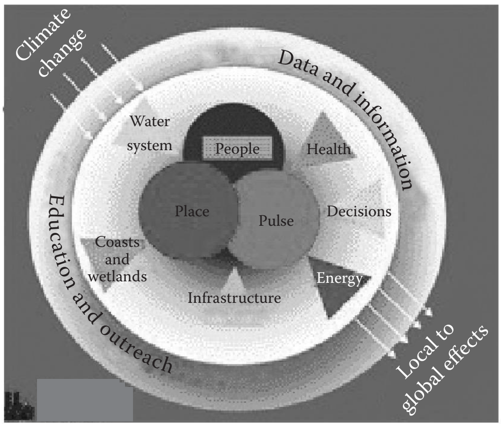

FIGURE 8.6 Relationship to climate change. (Courtesy of Cynthia Rosenzweig and Bill Solecki. From http://earthinstitute.columbia.edu.)

the UHI effect for the Global Hydrology and Climate Center, managed by NASA's Marshall Space Flight Center in Huntsville, Alabama. Quattrochi (1999) says that two major goals of their studies are to "understand how the characteristics of the urban landscape drive this urban heat island effect and how urbanization and growth shape the dynamics of the effect."

A description of the very first report of the UHI by Luke Howard, in 1820, states

> Howard was also to discover that the urban center was warmer at night than the surrounding countryside, a condition we now call the urban heat island. Under a table presented in *The Climate of London* (1820) of a nine-year comparison between temperature readings in London and in the country, he commented: 'Night is 3.7°F warmer and day 0.34° cooler in the city than in the country.' He attributed this difference to the extensive use of fuel in the city. (IPCC 2001)

In the late 1980s and early 1990s, scientists at the Lawrence Berkeley National Laboratories studied what came to be known as the UHI effect. In essence, they found that large urban centers are 3°C–7°C warmer in the summer than the surrounding countryside. This extra heat buildup was found to be due to

- Dark-colored pavement and roofs absorbing solar energy
- High concentration of air conditioners pumping heat outside
- Increased concentration of greenhouse gases caused by higher temperatures
- Dark-colored roofs causing 38% of the total increased heat

A study presented to the American Geophysical Union (AGU) documents that the concentration of concrete, large buildings, and other human activities artificially raises urban temperatures in such cities as Atlanta (see Figure 8.7) and Houston by an average of 10°F on hot summer days. The study supports a wide body of evidence

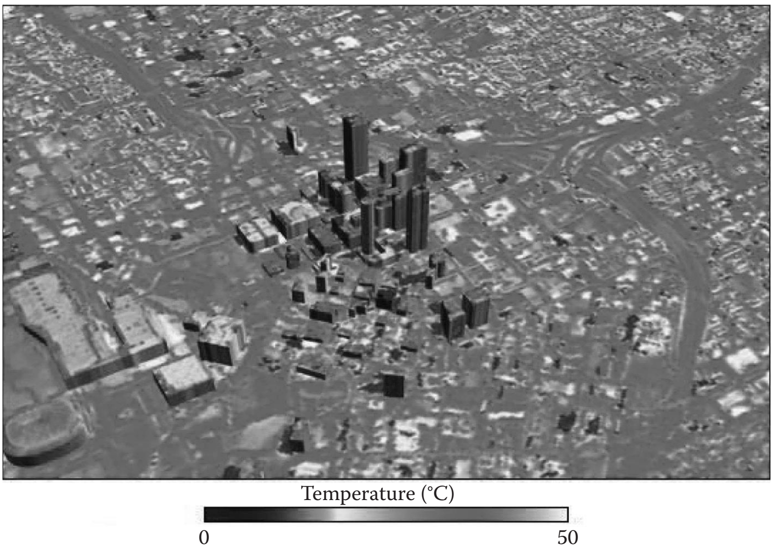

FIGURE 8.7 Thermal image of Atlanta, Georgia. On a scale of white to black, warmer areas appear white, whereas cooler areas appear black. Daytime air temperatures were only about 26.7°C (80°F), but some surface temperatures reached 47.8°C (118°F).

suggesting that ground-based temperature readings do not provide reliable evidence of significant global warming.

On a summer day in Houston, the urban temperature is approximately 8°F higher than the surrounding rural temperature. This difference is expected to increase as more and more green space is lost to roads, parking lots, and buildings. Even within a city, temperatures vary significantly, with large urban forests typically being 7°F cooler than the surrounding neighborhood. Dr. Quattrochi notes that the temperature of artificial surfaces can be 20°F–40°F higher than that of vegetated surfaces. The heat emitted by these surfaces creates a heat dome over cities (Steitz and Drachlis 1997).

The problem is exacerbated by the increasing development, pollution, and use of concrete that accelerate tree loss. In New York City, for example, 20% of its urban forest has been lost in the past decade (US Department of Energy 1993). The causes of the increased temperatures in cities are well understood. Concrete, asphalt, bricks, and buildings absorb and store solar energy (heat), creating UHIs. These surfaces then release this heat during the night, preventing significant overnight cooling in the city. The higher heat increases the volatilization of VOC (which is heat dependent), which then creates more pollution. The cloud of pollution lying over the city further traps heat.

Surface cover data help scientists determine an area's heat island. In May 1988, the US Department of Energy's Lawrence Berkeley National Laboratory (LBNL) modeled Baton Rouge's near-surface heat island (south-central Louisiana, east bank of the Mississippi River), which represents near-ground air temperatures as opposed to surface temperatures measured by thermal images. LBNL conducted this modeling analysis over an area several times larger than the city center. These simulations indicate that Baton Rouge's heat island ranges from 3.6°F to 7.2°F.

The severity and impact of the UHI phenomenon have been explored through different methods in Singapore. The startling difference in temperature between the rural and urban areas was shown clearly in satellite images. This indicates the occurrence of the UHI effect during the day in Singapore. The hot spots are normally observed on exposed hard surfaces in the urban context, such as the industrial area, airport, and central business district (CBD).

The satellite image also shows some cool spots, which are mostly observed on the large parks, the landscape in between the housing estates, and the catchment area. The survey routes near large green areas experienced lower temperatures compared with other land uses like the industrial areas, the residential areas, the CBD area, and the airport. Both the lowest temperature and the mean temperature, 24.3°C and 25.01°C, respectively, were observed in a well-planted area—Lim Chu Kang. It can be concluded that large green areas definitely have a positive effect on mitigating the UHI effect in the city (see Figures 8.8 and 8.9).

Other causes of a UHI are due to geometric effects of the built form. The tall buildings within many urban areas provide multiple surfaces for the reflection and absorption of sunlight, increasing the efficiency with which urban areas are heated. This is called the "canyon effect." Another effect of buildings is the blocking of wind, which also inhibits cooling by convection. Tall buildings and narrow streets can heat air trapped between them and reduce air flow (see Figure 8.10).

FIGURE 8.8 Temperature distribution of Japan.

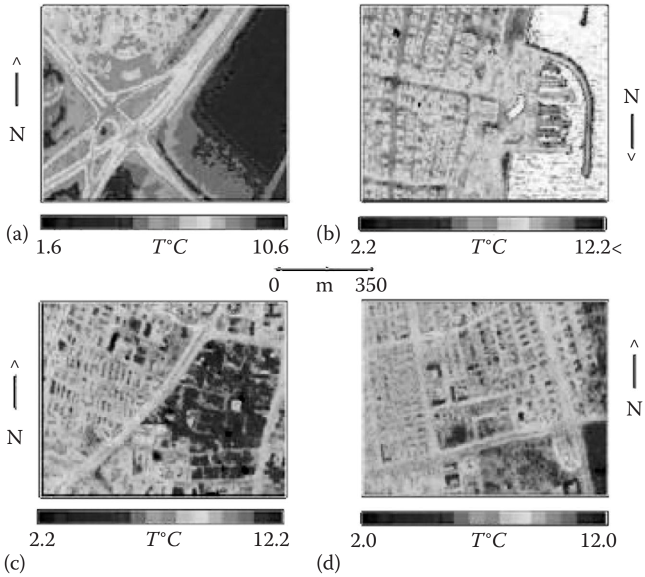

FIGURE 8.9 Thermal images of UHI of one of the warmest areas of Tel-Aviv as acquired from the airborne Inframetrics video radiometer during day and night and a year apart. Also provided is an air photo image of the area. (With the support of Belfer and Forter funds.)

It is useful to discuss the one aspect of the urban setting that influences the formation of the UHI effect. The urban canyon has two opposing effects: Not only can it increase the heat island effect by significantly reducing nighttime radiational cooling, but also it can decrease urban temperatures by shading pavements during the day. The ability of a surface to cool at night by emitting long-wave radiation into the

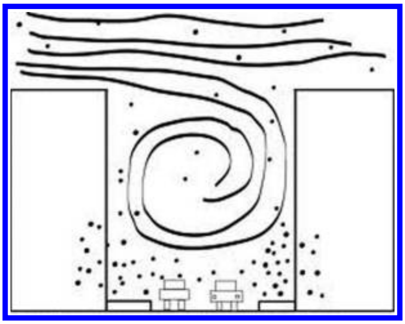

FIGURE 8.10 Air flow currents. (From http://web.mit.edu.)

sky depends on its "sky-view factor": the proportion of its viewing hemisphere that is occupied by sky rather than surrounding buildings. A pavement surrounded by tall buildings will have less exposure to the sky, so the buildings will block and absorb the heat emitted by the road and pavements. This prevents the heat from escaping the canopy air layer and exacerbating the heat island effect.

Marked differences in air temperature are some of the most important contrasts between the urban and rural areas shown. For instance, Chandler (1965) found that, under clear skies and light winds, temperatures in central London during the spring reached a minimum of 11°C, whereas in the suburbs, they dropped to 5°C (see Figure 8.11). The term "urban heat island" is used to describe the dome of warm air that frequently builds up over towns and cities (see Figure 8.12).

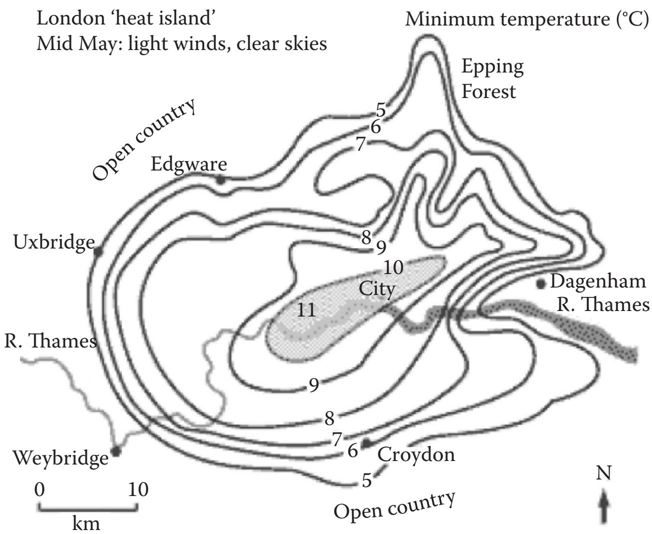

FIGURE 8.11 London heat island effect.

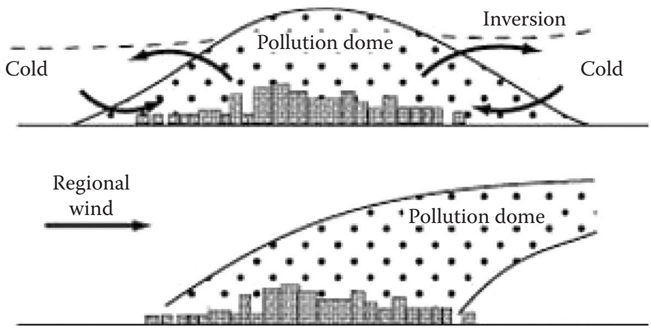

FIGURE 8.12 Urban pollution dome and plume.

The formation of a heat island is the result of the interaction of the following factors:

- The release (and reflection) of heat from industrial and domestic buildings.
- The absorption by concrete, brick, and tarmac of heat during the day and its release into the lower atmosphere at night.
- The reflection of solar radiation by glass buildings and windows. (The CBDs of some urban areas can therefore have quite high albedo rates [proportion of light reflected].)
- The emission of hygroscopic pollutants from cars and heavy industry acting as condensation nuclei, leading to the formation of clouds and smog, which can trap radiation. (In some cases, a pollution dome can also build up.)
- Recent research on London's heat island showing that the pollution domes can also filter incoming solar radiation, thereby reducing the buildup of heat during the day. (At night, the dome may trap some of the heat from the day, so these domes might be reducing the sharp differences between urban and rural areas.)
- The relative absence of water in urban areas, which means that less energy is used for evapotranspiration, and more is available to heat the lower atmosphere.
- The absence of strong winds to disperse the heat and bring in cooler air from rural and suburban areas. (Indeed, UHIs are often most clearly defined on calm summer evenings, often under blocking anticyclones.)

The precise nature of the heat island varies from urban area to urban area, and it depends on the presence of large areas of open space, rivers, the distribution of industries, and the density and height of buildings. In general, the temperatures are highest in the central areas and gradually decline toward the suburbs. In some cities, a temperature cliff occurs on the edge of town. This can be clearly seen in the heat profile for Chester, England, in Figure 8.13.

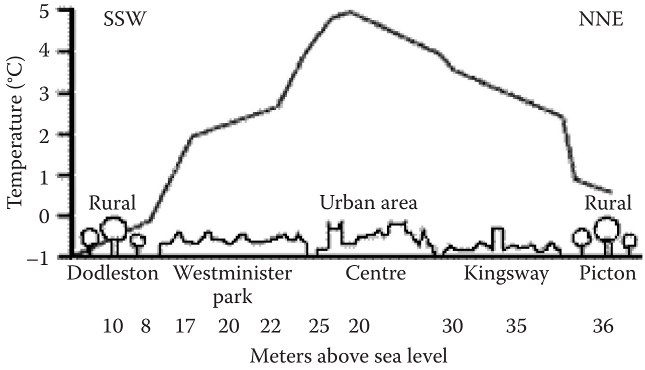

FIGURE 8.13 UHI in Chester, England. (From http://www.metoffice.gov.uk.)

8.5.3 Heat Island, Traffic, and Pollution Levels—Air Quality

Waste heat from vehicles, factories, and air conditioners may add warmth to their surroundings, further exacerbating the heat island effect. Some causes of a UHI are anthropogenic, though they are relatively minor in summer and generally in low- and mid-latitude areas. In winter and especially in high latitudes, when solar radiation is considerably smaller, these effects can contribute to the majority of UHI. As urban areas are often inhabited by large numbers of people, heat generation by human activity also contributes to the UHI. Such activities include the operation of automobiles, air-conditioning units, and various forms of industry. High levels of pollution in urban areas can also increase the UHI because many forms of pollution can create a local greenhouse effect (see Figure 8.14).

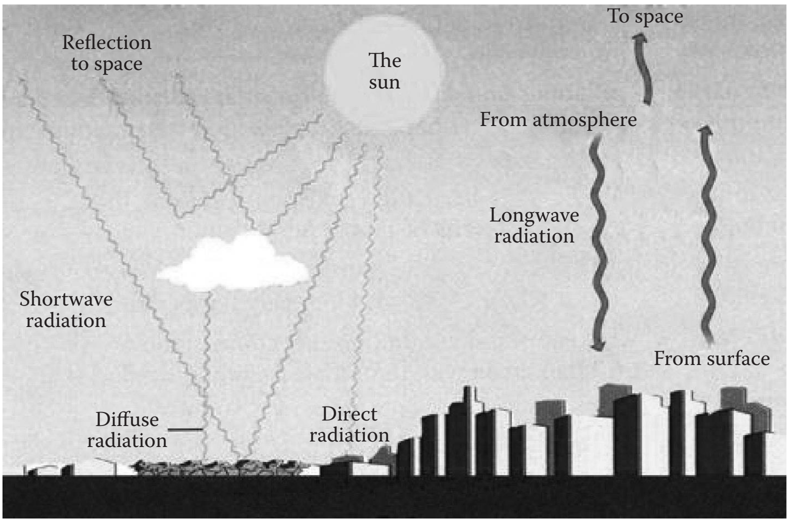

FIGURE 8.14 Surfaces and their effects on causal factors of UHI. (From http://www.ruf.rice.edu.)

Meteorologists Robert Bornstein and Qing Lu Lin (1999) from San Jose State University in California presented this finding at the annual meeting of the Association of American Geographers in Honolulu, Hawaii. Quattrochi and Luvall of NASA's Global Hydrology Center led this NASA-sponsored study. The Atlanta Land-Use Analysis: Temperature and Air Quality (ATLANTA) project began in 1996 in order to study the impact of UHIs on the environment.

Reradiated heat; waste heat generated by industry, vehicles, and mechanical equipment; and increased levels of air pollution have combined to raise urban temperature levels up to 8°C warmer than their surroundings on warm summer evenings. If estimates are correct, global warming will exacerbate the UHI effect by raising summer temperatures by an additional 5°C. Higher urban temperatures increase the instability of the atmosphere, which in turn can increase the chance of rainfall and severe thunderstorms. The city of Cologne, Germany, for example, receives 27% more rainfall than surrounding areas. In cities already plagued by overextended storm-water systems and combined sewage overflows, the problems caused by severe rainfall are likely to worsen with global climate change.

Higher temperatures also have a direct effect on air quality since heated air stirs up dust and airborne particulates as it rises. On a hot summer day, a typical insulated, gravel-covered roof in central Europe tends to heat up from 25°C to between 60°C and 80°C. This temperature increase means that a vertical column of moving air is created over each roof, which, for 1075 ft.^{2} (100 m^2) of roof surface area, can be moving upward at 0.5 m/s. Studies have shown that there is no vertical thermal air movement over grass surfaces. These surfaces will not heat up to more than 25°C.

Vehicle emissions and rising temperatures also contribute to an increase in ozone, a pollutant detrimental to the environment and human health (see Figure 8.15). During last year's ozone season in Atlanta, Georgia, which runs from the end of April to the end of September, the city suffered through 62 straight days of ozone

FIGURE 8.15 Smoke pollution in Mumbai, India. (Courtesy of Applied Power Corporation.)

alerts. Quattrochi (1999) says that, based on models, there is potential for a temperature decrease of 2°C in Atlanta to lower the ozone by 10%–14%, a significant drop. The increase in urban temperature contributes to an increase in ozone, a particularly destructive type of smog. Ozone interferes with photosynthesis, the process by which plants make food, and damages the lungs of people and animals.

More recently, Lindzen (2006, p. A14), who still opposes the idea that humans have caused global warming, has acknowledged that the warming itself is real: "First, let's start where there is agreement. The public, press and policy makers have been repeatedly told that nineteenth century levels of carbon dioxide (CO_2) in the atmosphere have increased by about 30% over the same period and CO_2 should contribute to future warming. These claims are true."

UHIs are not only uncomfortably hot but are also smoggier. Smog is created by photochemical reactions of pollutants in the air. These reactions are more likely to occur and intensify at higher temperatures. In Los Angeles, for example, for every degree Fahrenheit, the temperature rises above 70°F; the incidence of smog increases by 3%.

Higher ambient temperatures in heat islands also increase air-conditioning energy use. As power plants burn more fossil fuels, they increase both pollution levels and energy costs. The impact of these pollution levels is seen in smog. The formation of smog is highly sensitive to temperatures; the higher the temperature, the higher the formation and, hence, the concentration of smog (see Figures 8.16 and 8.17). In Los Angeles, at temperatures below 70°F, the concentration of smog (measured as ozone) is below the national standard. At temperatures of about 95°F, all days are smoggy. Cooling the city by about 5°F would have a dramatic impact on smog concentration. An additional consequence is that the probability of smog also increases by 5% for every 0.5°F rise in daily maximum temperature above 70°F. An important theoretical premise is that increments in surface thermal emissions directly contribute to an elevation in atmospheric temperatures, with significant implications for air quality and human health.

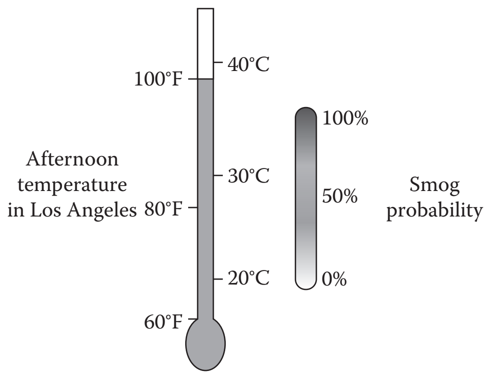

FIGURE 8.16 Smog and temperature. (From http://heatisland.lbl.gov/.)

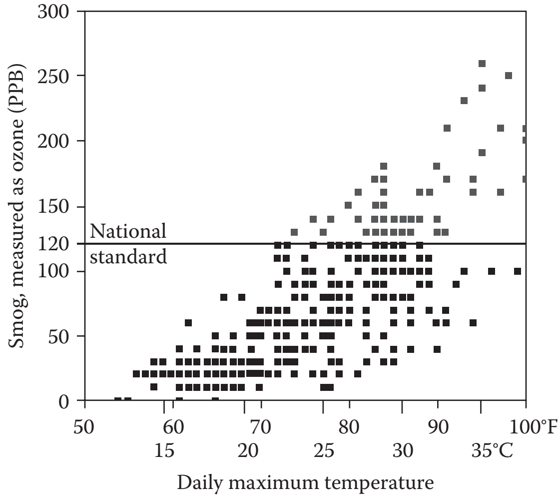

FIGURE 8.17 Measured at Los Angeles, North Main, 1985; as temperature rises, so does the likelihood that smog will exceed the national standard. (From http://heatisland.lbl.gov.)

8.5.4 Loss of Tree Protection

Displacing trees and vegetation minimizes the natural cooling effects of shading and evaporation of water from soil and leaves (evapotranspiration). There are fewer trees, shrubs, and other plants to shade buildings, intercept solar radiation, and cool the air by evapotranspiration. The energy balance is also affected by the lack of vegetation and standing water in urban areas, which inhibit cooling by evapotranspiration.

Heat islands are created through the process of urbanization (see Figure 8.18). As a city grows, trees, which normally reduce the amount of heat and smog, are cut down to make room for commercial development, roads, and suburban growth. Plants and soil absorb heat during the day and then carry the heat away through evaporation. In Atlanta, urban development has increased so drastically between 1973 and 1992 that almost 380,000 ac of forest was cleared to accommodate that growth (see Figure 8.19). Heat islands are created when city growth alters the urban

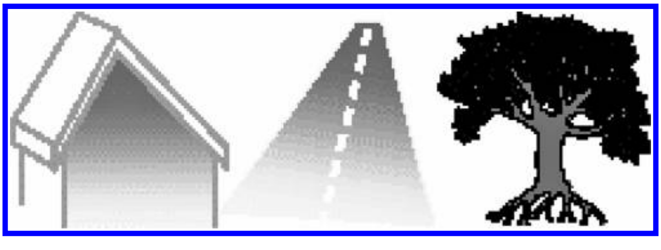

FIGURE 8.18 Schematic representation of the causes of UHI effect. (From http://www.heatislandeffect/EPA.gov.)

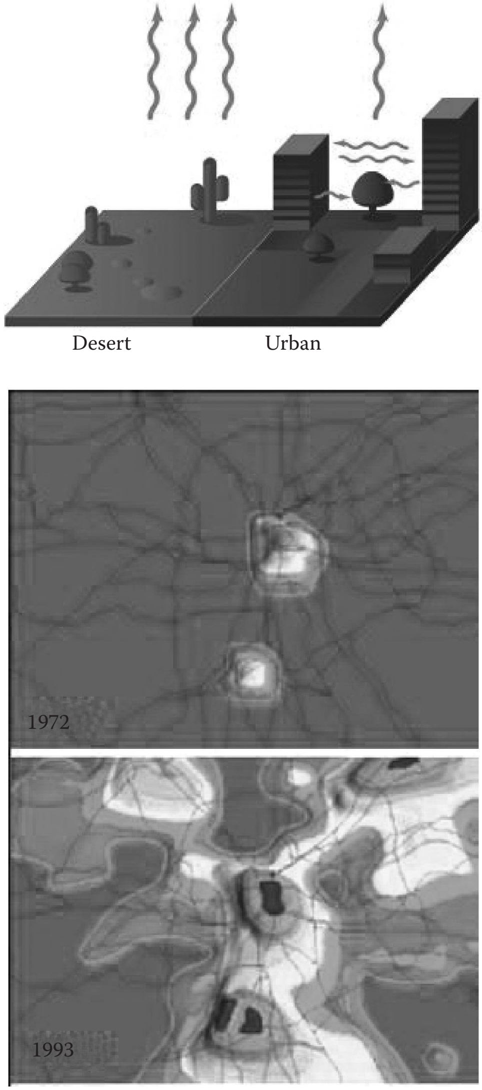

FIGURE 8.19 Atlanta in 1972 and 1993. The growing UHI corresponds to the replacement of trees and other vegetation with concrete, asphalt, and other surfaces. The centers of the heat islands in 1993 are up to 12°C hotter than the surrounding countryside.

fabric by substituting man-made asphalt roads and tar roofs and other features for forest growth. Trees provide shade and cool the air through evaporation.

Urban forests are a vital component of the urban ecosystems. Very little information is available to planners and legislators in India regarding the costs and benefits of urban trees because few Indian studies have been carried out. The pollutant-removing, oxygen-producing, and heat-mitigating qualities of trees were known many decades ago, but the quantification of these abilities has begun only recently.

Plants play a crucial role in the survival of life on our planet. Through the photosynthesis process, which takes place within green leaves and stems, plants convert carbon dioxide, water, and sunlight/energy (solar radiation) into oxygen and glucose. Plants supply humans and other animals with oxygen and food, and animals, in turn, produce the carbon dioxide and manure required by the plants. Studies have shown that one mature beech tree (80–100 years old), with a crown diameter of 15 m, shades 170 m^2 of surface area, has a combined leaf surface area of 1600 m^2, and creates 1.71 kg of oxygen and 1.6 kg of glucose every hour (using 2.4 kg of carbon dioxide, 96 kg of water, and 25.5 kJ of heat energy). This level of production equals the oxygen intake of 10 humans every hour.

One of the crucial elements in selecting plant types and densities is the green leaf and stem surface area available for photosynthesis. For example, 25 m^2 of leaf surface area produces 27 g of oxygen per hour during the day, which equals the amount of oxygen that a human would require for the same time period. However, considering the effects of nature, nighttime (no sunlight), and winter (no green leaves on deciduous plants), 150 m^2 of leaf surface area would be required to balance the human intake of oxygen for 1 year (Peck et al. 1999).

Scientists used satellite data as well as sensors onboard a Learjet to study urban growth trends and effects on weather. Data showed that temperatures in parking lots could exceed 120°F, whereas small tree islands in the same lot had temperatures of only 89°F. NASA scientists are using space age technology to understand how characteristics of the urban environment create UHIs.

A study by Taha (1997) found that the primary contributors to UHIs are reduced vegetation and darker surfaces. Replacing vegetation with paved surfaces leads to higher air temperatures because the sun's energy that was previously used for evapotranspiration is now used to heat these surfaces. These surfaces usually have a lower albedo and thus reflect less of the sun's rays. Pavement, especially dark pavement, sitting in the hot sun during the day will readily absorb the sun's heat, and then it will release that heat into the air to warm the environment around it.

In large cities, land surfaces with vegetation are relatively few and are replaced by nonreflective, water-resistant surfaces such as asphalt, tar, and building materials that absorb most of the sun's radiation. These surfaces hinder the natural cooling that would otherwise take effect with the evaporation of moisture from surfaces with vegetation. The UHI occurrence is particularly pronounced during summer heat waves and at night when wind speeds are low and sea breezes are light. During these times, New York City's air temperatures can rise 7.2°F higher than in surrounding areas.

In one project, NASA researchers set out to recommend ways to reduce the UHI effect in New York City. They looked at strategies such as promoting light-colored surfaces such as roofs and pavements that reflect sunlight, planting "urban forests," and creating "living roofs" on top of buildings where sturdy vegetation can be planted and thrive. Using a regional climate computer model, the researchers wanted to calculate how these strategies lower the city's surface and close-to-surface air temperatures and what the consequences of these strategies would be on New York's energy system, air quality, and the health of its residents.

The researchers conducted a citywide case study over the summer of 2002 to measure changes in air temperatures (see Figure 8.20). They also used six smaller case studies

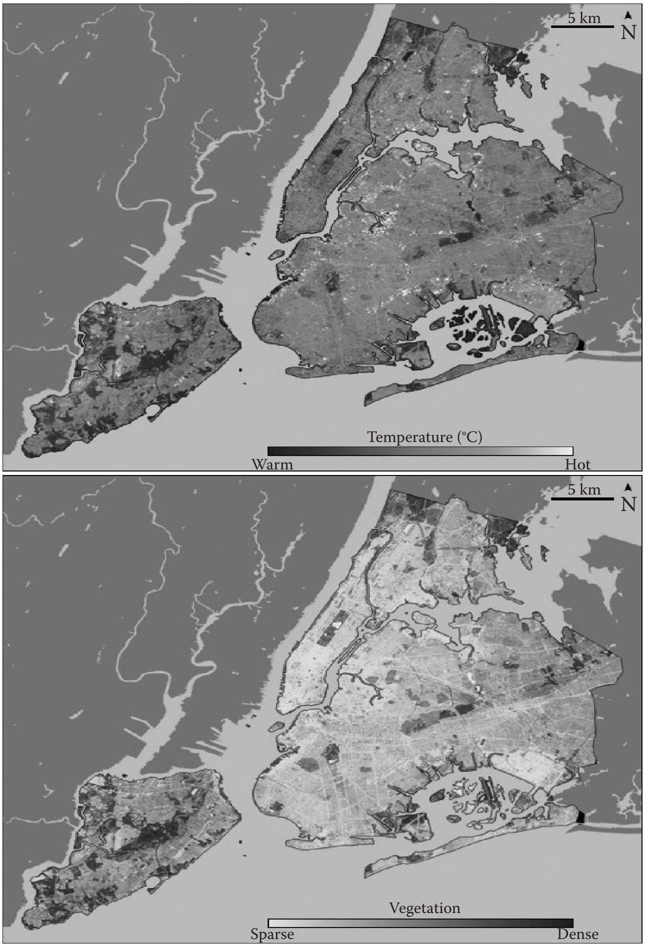

FIGURE 8.20 Thermal (a) and vegetation (b) infrared satellite data measured by NASA's Landsat 7 Enhanced Thematic Mapper Plus on August 14, 2002, one of the hottest days in New York City's summer. A comparison of the images shows that where vegetation is dense, temperatures are cooler.

during the same period in places like lower Manhattan, the Bronx's Fordham section, Brooklyn's Crown Heights section, and the Maspeth section of Queens. The areas were chosen for the different ways in which land was used and their nearness to areas with high electrical use. They also had warmer than average near-surface air temperatures, called "hot spots," and boasted available spaces to test ways to reduce the UHI effect.

8.5.5 Use of Asphalt in Road Topping

Asphalt roads and tar roofs absorb and hold nearly all of the heat around them. There is little material in urban areas that reflects heat. Atlanta is 5°F–8°F hotter than the outlying areas, and this excess heat produces increased rainfall and thunderstorms.

Concrete roads can be used to mitigate the UHI because their albedo value is between 0.1 and 0.35; asphalt has an albedo value between 0.05 and 0.2. Thin concrete can be placed on the existing asphalt roads. This will have greater wearing resistance than asphalt, resulting in economically viable solutions as well as increased albedo values.

8.5.6 Greenhouse Gas Emissions—Ozone Depletion

Greenhouse gas emissions, such as carbon dioxide, methane, and nitrous oxide, contribute to global warming and climate change. According to the US-based think tank, the World Resources Institute, India was responsible for over 4% of total emissions in 2000—making the country the sixth largest emitter in the world. Emissions are set to rise further still over the next 20 years as the Indian economy rapidly develops. Both the International Energy Agency and the US Energy Information Administration predict over 90% growth in carbon dioxide emissions alone by 2025.

According to Bhattacharya and Mitra (2004), carbon dioxide emissions account for over 60% of greenhouse gases released in India. Most of this comes from the energy sector burning fossil fuels, such as coal, oil, and natural gas (see Table 8.1 and Figures 8.21 through 8.23).

Studies have shown that urban streets with trees have only 10%–15% of the total dust particles found on similar streets without trees. In Frankfurt, Germany, for example, a street without trees had an air pollution count of 10,000–20,000 dirt particles per liter of air, but a street with trees in the same neighborhood had an air pollution count of only 3000 dirt particles per liter of air.

Shukla (2006) predicts a rise of almost 10 times the current levels. According to A. P. Mitra, an emeritus scientist at Delhi's National Physical Laboratory and a former director general of the Council of Scientific and Industrial Research, a fourfold

TABLE 8.1
Comparison of Indian Greenhouse Gases to Other Emitters

	1990		2000	
Country	**Million Tonnes Carbon Dioxide Equivalent**	**Percent of World Total**	**Million Tonnes Carbon Dioxide Equivalent**	**Percent of World Total**
USA	5630.00	14.62	6525.20	15.81
China	3973.50	10.32	4890.40	11.85
Indonesia	2498.80	6.49	3065.60	7.43
Brazil	2641.80	6.86	2223.20	5.39
Russian Federation	2916.00	7.57	1969.40	4.77
India	1305.00	3.39	1843.80	4.47
Japan	1216.70	3.16	1321.00	3.20
Germany	1198.50	3.11	1009.40	2.45

Note: Indian greenhouse gas emissions compared to other significant emitters.

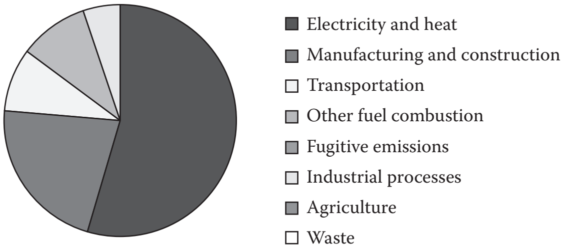

FIGURE 8.21 Carbon dioxide emissions in India by sector in 2000. (From Climate Analysis Indicators Tool, version 3.0. World Resources Institute.)

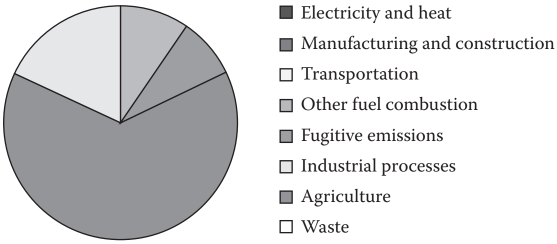

FIGURE 8.22 Methane emissions in India by sector in 2000. (From Climate Analysis Indicators Tool, version 3.0. World Resources Institute.)

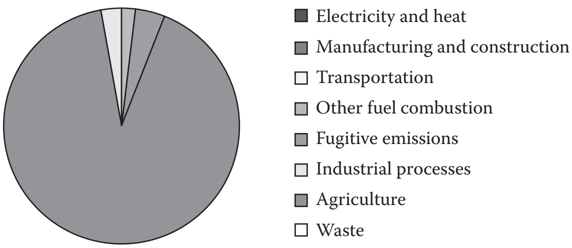

FIGURE 8.23 Nitrous oxide emissions in India by sector in 2000. (From Climate Analysis Indicators Tool, version 3.0. World Resources Institute.)

increase in the country's gross domestic product (GDP) would require a 2.8-fold increase in carbon dioxide emissions, 1.3 times more methane, and 2.6 times more nitrous oxide unless action is taken. The World Resources Institute, a US-based environmental think tank, estimates that by 2025, India will rank fourth in the world for total greenhouse gas emissions.

8.5.7 Population Increase—Demographic Changes

In 2005, 50% of the world's population lived in cities consuming over 75% of the world's energy; as human development (as measured by the United Nations [UN] index) progresses, energy use will increase faster than the increase in population. By

2030, it is predicted that over 60% of the world's population will live in cities with this percentage continuing to rise to the end of the century. Urban areas are particularly vulnerable to the effects of global warming, particularly extreme weather events such as floods, storm surges, drought, and heat waves.

8.5.7.1 Population Growth, Consumption Patterns, and Emissions

The UN projects that world population will, under the most likely scenario, have increased from 5.3 billion in 1990 to 6.3 billion by 2000, growing thereafter to 8.5 billion in 2025, 10.0 billion in 2050, and 11.2 billion in 2075. The World Bank's projections are very similar. Nearly all of this growth is anticipated in today's developing countries (see Figure 8.24). Increases in world population would mean increased global demand for energy, which, with current energy technologies, would result in increased greenhouse gas emissions. Population growth would also probably result in further deforestation and expansion of irrigated agriculture; both activities are sources of greenhouse gases. Population policy is therefore becoming increasingly important for long-range planning within developing countries. Therefore, the industrial growth that would be necessary to meet the population requirements, if population levels were to continue to rise so rapidly, would place enormous stresses on the environment in future decades (World Bank 1992).

Surface-based temperature readings reflect localized human population growth rather than any significant increase in global temperatures. Researcher David Streutker analyzed two sets of infrared temperature measurements for the city of Houston, Texas. The findings were published in *Remote Sensing of the Environment*, a research journal for environmental scientists (Rice University Department of Physics and Astronomy). By comparing ground-based and satellite temperature readings, Streutker demonstrated that over the course of 12 years (between 1987 and 1999), the Houston UHI effect increased nearly a full degree Celsius. "Urban population growth, rather than any external warming, explained the rise in temperatures in and around Houston," said Streutker.

A study recently published in *Australian Meteorological Magazine* documented that the UHI effect artificially raises temperature readings in towns as small as 1000 people. According to the Center for the Study of Carbon Dioxide and Global Change, "Changes in population, which have generally been positive nearly everywhere in the world over

FIGURE 8.24 Center of São Paulo, one of the largest metropolises in the world. (From http://www.urbanization/saopaulo.)

this period, could easily explain" why ground-based temperature readings, usually taken in and near cities, show an apparent warming trend that is not substantiated by other data.

An AGU study bolsters the evidence that surface-based temperature readings reflect localized human population growth rather than any significant increase in global temperatures. "The majority of evidence is pointing to some sort of urban modification," said Daniel Rosenfield of Hebrew University.

India is a part of the global trend toward increasing urbanization in which more than half of the world's population are currently residing in cities and towns. According to the 2001 census, there were 4378 towns and cities in India and 35 metropolitan cities having a population of over 1 million. In India, of the total population of 1027 million, as of March 1, 2001, about 742 million (72.2%) lived in rural areas and 285 million (27.8%) in urban areas. The percentage growth of population in rural and urban areas during the last decade was 17.9% and 31.2%, respectively. It is important to note that the contribution of the urban sector to GDP is currently expected to be in the range of 50%–60%. The increased urbanization seen today is a result of this overall growth. With a shift in demography toward urban areas (see Figure 8.25), deterioration of air quality, formation of heat islands, and poorly constructed dwelling units make over urban centers prone to weather hazards. Anthropogenic heat production figures for the top 20 cities in the United States are given in Table 8.2.

We need to be aware that a lower population density may translate into additional heat generated by a greater use of transportation energy. As Houston grows, the population density should not be allowed to increase radically if we do not want the temperature to increase significantly with it. Increasing at a rate of 0.25°F–2°F (0.1°C–1.1°C) per decade, the heat

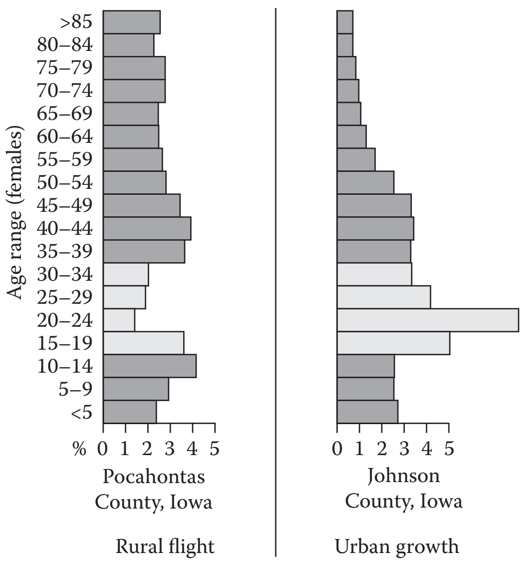

FIGURE 8.25 Population age comparison between rural Pocahontas County, Iowa, and urban Johnson County, Iowa, illustrating the flight of young adults to urban centers in Iowa.

TABLE 8.2
Anthropogenic Heat Production for the Top 20 Cities in the United States

Rank	Place	Population	Land Area (mi.^{2})	Persons/ mi.^{2}	Persons/ m^2	Anthropogenic Heat (kWh/m^2 day)
1	New York City, NY	7,322,564	308.9	23,705	0.00853	2.3
2	Los Angeles, CA	3,485,398	469.3	7427	0.00267	0.72
3	Chicago, IL	2,783,726	227.2	12,252	0.00441	1.19
4	Houston, TX	1,630,553	539.9	3020	0.00109	0.29
5	Philadelphia, PA	1,585,577	135.1	11,736	0.00422	1.14
6	San Diego, CA	1,110,549	324	3428	0.00123	0.33
7	Detroit, MI	1,027,974	138.7	7411	0.00267	0.72
8	Dallas, TX	1,006,877	342.4	2941	0.00106	0.29
9	Phoenix, AZ	983,403	419.9	2342	0.00084	0.23
10	San Antonio, TX	935,933	333	2811	0.00101	0.27
11	San Jose, CA	782,248	171.3	4567	0.00164	0.44
12	Baltimore, MD	736,014	80.8	9109	0.00328	0.88
13	Indianapolis, IN	731,327	361.7	2022	0.00073	0.2
14	San Francisco, CA	723,959	46.7	15,502	0.00558	1.5
15	Jacksonville, FL	635,230	758.7	837	0.0003	0.08
16	Columbus, OH	632,910	190.9	3315	0.00119	0.32
17	Milwaukee, WI	628,088	96.1	6536	0.00235	0.63
18	Memphis, TN	610,337	256	2384	0.00086	0.23
19	Washington, DC	606,900	61.4	9884	0.00356	0.96
20	Boston, MA	574,283	48.4	11,865	0.00427	1.15

island effect within urban cores of rapidly growing metropolitan regions may double within 50 years (McPherson 1994). In light of roughly 2.9 billion new residents projected to arrive in urban regions between 1990 and 2025, there is a pressing need to ascertain the implications of urban warming for metropolitan regions and to identify potential strategies to counteract regional climate change (World Resources Institute 1990).

8.5.8 Urban Development and Infrastructure Activities of Cities

8.5.8.1 Excess Energy Consumption in Buildings

Unplanned and unsustainable urban development has led to severe environmental pressures. The green cover and groundwater resources have been forced to give way to rapidly developing urban centers. Modern buildings built in our cities have high levels of energy consumption because of the requirements of air conditioning and lighting. Another consequence of UHIs is the increased energy required for air conditioning and refrigeration in cities that are in comparatively hot climates.

Yoshinobu Ashie, chief researcher at the Building Research Institute in Tsukuba, Japan, said that in the late nineteenth century, Japan began heavily importing Western culture and technology that radically transformed lifestyles. Modern technology brought

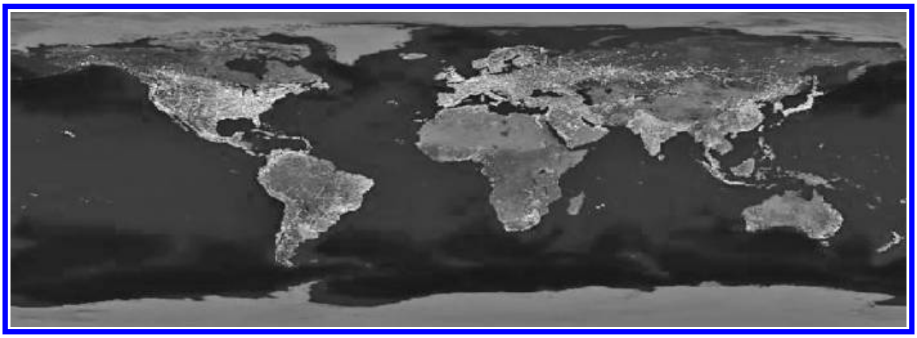

FIGURE 8.26 An image taken from Astronomy Picture of the Day of the surface of the earth. It is a composite of hundreds of satellite images taken at night. It is a perfect indicator of urbanization on earth. The greatest urbanization is over the continental United States, Europe, India, Japan, Eastern China, and primarily coastal South America.

electrically powered fans and air conditioners. Skyscrapers and big apartments crowded the city, adding to the increasing heat. Ashie said that there was a vicious cycle: The rising heat spurs heavier use of air conditioning, which in turn generates more heat.

Materials that absorb heat hold in the heat long after the sun sets, keeping the cities hotter for longer periods of time. Atlanta experiences early morning rain showers because UHIs retain their temperature long after nightfall. This causes an even greater difference in temperature between urban and outlying areas. While much of the growth in Atlanta has been residential in nature, Quattrochi (1999) cautions that commercial and residential development often go hand in hand. With no indication that urban sprawl will slow in the near future, scientists are searching for ways to curb UHIs (see Figure 8.26).

8.5.8.2 Sustainability and Development

What is sustainable development? It is environmental, economic, and social well-being for today and tomorrow. Sustainable development has been defined in many ways, but the most frequently quoted definition is from "Our Common Future," also known as the Brundtland Report:

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
>
> It is made up of two key concepts:
>
> - The concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given;
> - The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

All definitions of sustainable development require that we see the world as a system—a system that connects space and a system that connects time.

Sustainable building maximizes use of efficient building materials and construction practices; optimizes use of on-site sources and sinks by bioclimatic architectural practices; uses minimum energy to power itself; uses efficient equipment to meet its lighting, air-conditioning, and other needs; and maximizes use of renewable sources of energy. Sustainable or "green" building is an integrated approach to the design, construction, and operation that minimizes negative environmental effects.

On April 8, 2005, Washington became the first US state to enact a law requiring public buildings to be constructed with standards encouraging energy conservation and recycling. Governor Christine Gregoire signed the historic bill into law at Washington Middle School in Olympia, which became among the first buildings in the state to incorporate "green" standards (http://www.theolympian.com/home/news/20050409/southsound/122219.shtml).

The basic precepts of green building are based on tenets of sustainability, such as the Coalition for Environmentally Responsible Economies (CERES) and Hannover Principles buildings, which are models of resource conservation:

- Treatment of water and energy
- Efficiency and renewable energy use
- Minimizing waste and preventing pollution
- Reducing operation and maintenance costs

Stabilization of population would contribute toward sustainable development to a large extent by reducing the population pressure on resource utilization.

8.5.8.3 Unplanned Urban Development

Heat islands form as cities replace natural land cover with pavement, buildings, and other infrastructure. These changes contribute to higher urban temperatures in a number of ways. According to the country's report to the UN Framework Convention on Climate Change (UNFCC 2004), India would continue to meet its development needs but is concerned about the likely impact of severe floods on its infrastructure, such as roads and railways, as well as the likely increase in electricity needs to pump underground water and cool houses and offices in hot areas. Since considerable investment is planned for improving infrastructure, especially for irrigation and technology in the agriculture sector, it will have a beneficial effect on the greenhouse gas emission from this sector by improving reduced energy consumption.

Protecting biodiversity is one of the basic tenets of sustainable development. The government of India has initiated and implemented several activities aimed at protecting biodiversity. Sustainable development and concern for the environment are major concerns and driving forces behind the Indian planning process. Integrating climate change concerns with the national planning process is important.

According to TERI, modern buildings built in our cities have high levels of energy consumption because of requirements of air conditioning and lighting. At the national level, domestic and commercial buildings account for more than 30% of annual electricity consumption. TERI studies show that air conditioning and lighting are the two end uses in the building sector that account for maximum energy consumption. About 50%–60% of energy consumed in a fully air-conditioned building is by air conditioning, followed by lighting, which consumes 20% of the energy. TERI's experience shows that over 20% of energy savings is possible in existing buildings by retrofitting them with efficient lighting, air conditioning, and electrical

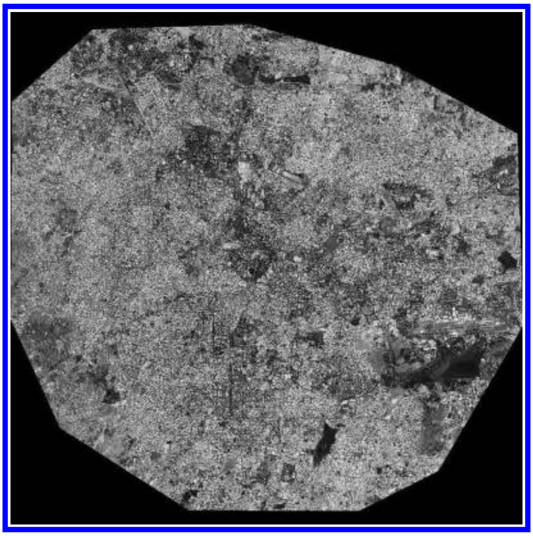

FIGURE 8.27 Satellite imagery showing all the various surfaces causing UHI effect over Bangalore. All areas of concrete surfaces are shown covering most of the area of Bangalore city limits. (Courtesy of Remote Sensing.)

systems. New buildings can save up to 50% energy by appropriate design interventions in building envelope, lighting, and air-conditioning systems. In a recently concluded study by TERI in an office building in Delhi, annual energy consumption of 400 kWh/m^2 (kilowatt-hour per square meter) was recorded. It was further analyzed and inferred that 30% of its present energy consumption could be reduced by adopting efficiency measures such as chiller and pump replacement, lighting retrofit, and resizing of the capacitor bank.

In Bangalore, tall avenue trees are giving way to glass and metal-clad buildings of a commercial nature. The growing transportation needs, along with the increased traffic density, have also necessitated building a large number of grade separators (see Figure 8.27).

8.5.9 Use of Darker and Nonreflective Materials

Causes of the heat island effect include dark surfaces, which absorb more heat from the sun, and less vegetation to provide shade and cool the air. Buildings and pavement made of dark materials absorb the sun's rays instead of reflecting them away, causing the temperature of the surfaces and the air around them to rise. Materials commonly used in urban areas, such as concrete and asphalt, have significantly different thermal bulk properties and surface radiative properties (albedo and emissivity) than the surrounding rural areas. This initiates a change in the energy balance of the urban area, often causing it to reach higher temperatures (measured both on the surface and in the air) than its surroundings. These higher temperatures contribute to a trend of increasing temperatures.

8.5.10 Roofing Materials

The Heat Island Group has monitored buildings in Sacramento with light-colored, more reflective roofs. We found that these buildings used up to 40% less energy for cooling than buildings with darker roofs. The Florida Solar Energy Center performed a similar study that also showed up to 40% cooling energy savings. The Heat Island Group continues to monitor buildings and measure or simulate the effects of increased roof reflectivities for

- Different types of buildings
- Different climate zones and seasons
- Different roof insulation levels, angles, and orientations

This important research is needed to find the best ways to save energy and money using reflective roofing.

8.5.10.1 Various Materials in Sunlight

Outdoor measurements on the 12 samples in the graph in Figure 8.28 show how the temperature rise in full sun is inversely correlated with the solar reflectance values measured with our instruments in the laboratory. Materials with emittance of approximately 0.9 fall near the straight line. Materials with lower emittance, particularly galvanized steel, fall above the line due to their limited ability to emit thermal radiation (Berdahl and Bretz 1997). There are, unfortunately, many problems in measuring emittance.

Roof heat transfer. The surface temperature of a roof is determined mainly by the vigorous heat flows at the outside surface. Of these external energy flows, convective cooling is the least precisely known. The solar and infrared radiative cooling can be readily calculated if the solar reflectance and infrared emittance are known.

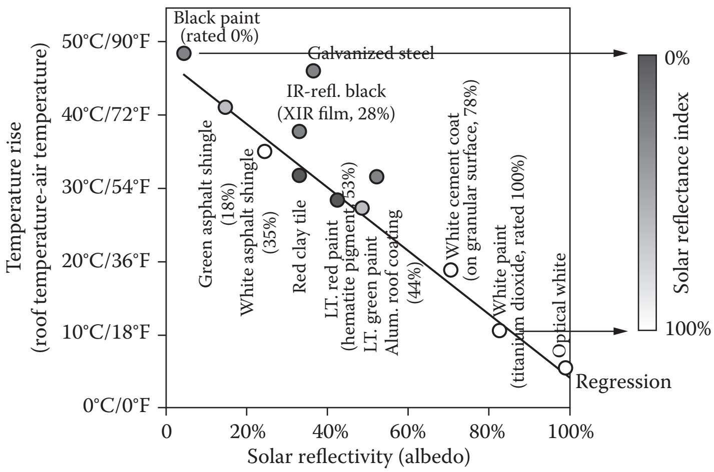

FIGURE 8.28 Various materials in sunlight. (From Berdahl, P., and S. Bretz, *Energy and Buildings,* 25: 149, 1997.)

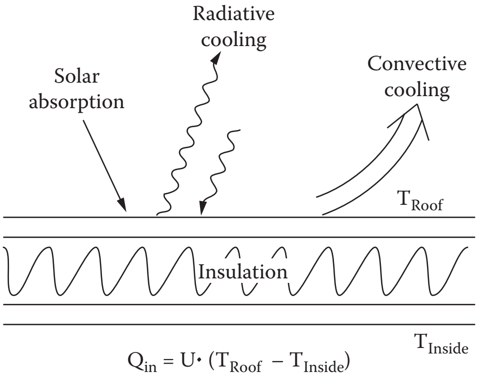

FIGURE 8.29 Roof heat flows. Diagram of heat flows into and out of a roof. The heat flowing through a roof is a function of the difference in temperatures on either side of the roof. (From http://heatisland.lbl.gov/).

Once the roof temperature is known, the heat flow leaking into the interior is readily computed (see Figure 8.29). Decreasing a roof's emittance may lead to an increase in energy use. Energy-efficient roofing systems can reduce roof temperatures significantly during the summer.

Materials specialist Paul Berdahl is developing a new rating system called the solar reflectance index (SRI) to measure how hot materials are in the sun. The extremes of white and black paint (on the graph in Figure 8.30) define the SRI. Solar reflectivity is measured according to ASTM E903. Traditional roofing materials have an SRI of between 5% (brown shingles) and 20% (green shingles). White shingles with SRIs of around 35% were popular in the 1960s, but they lost favor because they get dirty easily. The current trend is to make white shingles more reflective. Berdahl compiles and measures the solar reflectance and infrared emittance of roofing materials.

Cool or heat-reflective roofs

- Reduce the need for air-conditioning costs during the summertime
- Can reduce the need for roof insulation in southern climes
- Moderate the local microclimate, thereby helping reduce the UHI effect (in turn, reducing air-conditioning energy use, pollution, and global warming)

Heat-reflective roofs are not simply light-colored roofs. To be a true heat-reflective roof, the roof surface must possess two qualities:

1. High albedo or light reflectivity
2. High emissivity or the ability to release absorbed energy

The relative albedos and emissivities of various roof surfaces are shown in Table 8.3.

Widespread use of heat-reflective roofing in urban areas can potentially lead to significant reductions in the UHI effect and even help reduce global warming. For this reason, heat-reflective roofs are evaluated and recognized by both the Energy

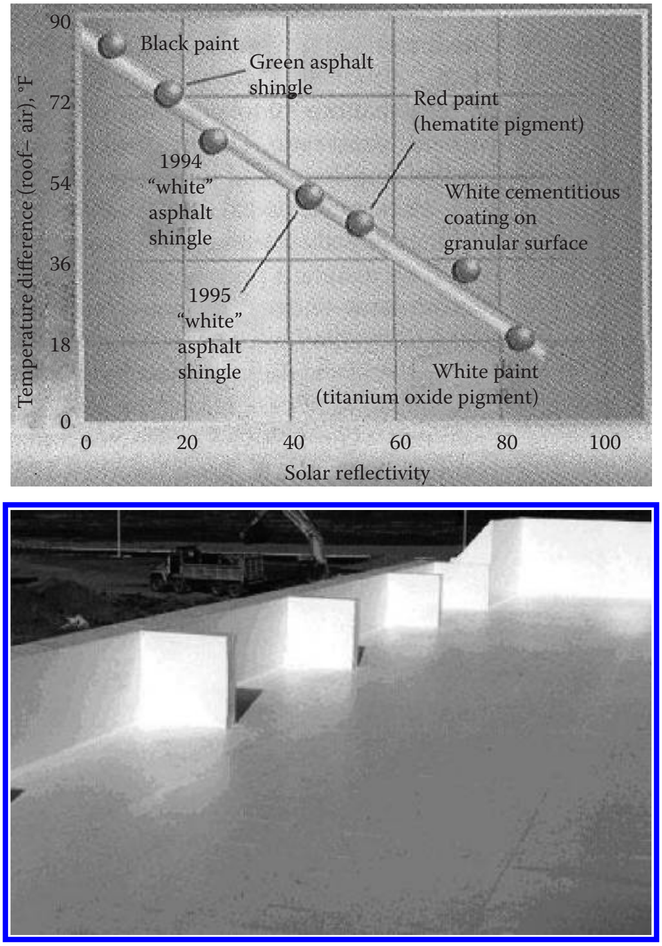

FIGURE 8.30 White, heat-reflective membranes can help reduce the UHI effect.

Star™ and the Leadership in Environmental Engineering and Design programs. In addition, certain jurisdictions provide tax credits or other monetary incentives for building owners choosing a heat-reflective roof.

8.5.11 Paving Materials

Pavements are critical to transportation in all of its aspects—walking, riding in passenger vehicles, carrying goods in commercial vehicles, providing mobile services, and parking. They account for a significant percentage of the land surface in an urban area. By altering land cover, pavements have important localized environmental effects in urban areas. As with roofing materials, paving materials can reach 150°F in the daytime, radiating this excess heat during both day and night into the air

TABLE 8.3
Relative Albedos and Emissivities of Various Roof Surfaces for All Materials Except Single-Ply Membranes

Material	Albedo	Emissivity
Clean pea gravel	0.72	0.28
Gray pigment	0.03	0.87
Bright galv. steel	0.35	0.13
Aluminum paint	0.80	0.27–0.67
White paint on aluminum	0.80	0.91
Black ethylene-propylene-diene terpolymer (EPDM) membrane	0.04	0.88
White hi-tuff membrane	0.78	0.90

Source: *Implementation of Solar-Reflective Surfaces; Materials and Utility Programs.* Lawrence Berkeley Laboratory, June 1992.

in the urban canopy layer (as well as heating storm water that reaches the pavement surface). Due to the large area covered by pavements in urban areas, they are an important element to consider in heat island mitigation.

Frequent storms can cause flooding because paved ground does not allow water to soak into the soil (Environment Ministry of Japan 2001). In place of conventional asphalt for road pavement, the metropolitan government has also been laying a new type of concrete block that retains moisture. The material properties of pavements cause them to absorb and store a larger amount of heat than vegetated land cover. The impervious nature of most pavements reduces cooling due to evaporation in comparison to vegetation. As a result, pavements become considerably hotter than ambient canopy temperature and radiate this excess heat into the canopy layer throughout the day and into the night.

As part of a heat island reduction strategy, cool pavements contribute to the general benefits of heat island mitigation, including increased comfort, decreased energy use, and likely improved air quality. Cool pavements also can be one component of a larger sustainable pavements program or a "green" transportation infrastructure.

The cool pavement mechanisms are based on the idea that by increasing the reflectance of the pavement surface, less sunlight will be absorbed, lowering the daytime temperature of the pavement. This lowered temperature would result in lower air temperature near the ground level. Cool pavement strategies seek to control the temperature of the pavement (and hence its ability to transfer heat to the air above) by controlling one or more of the material properties that influence the way pavements absorb, store, and radiate heat.

8.5.12 Climate and Topography

In addition to these factors, heat island intensities depend on an area's weather and climate, proximity to water bodies, and topography. Scientists warn that big Japanese cities may soon become too hot to live in and that preventive measures must be taken immediately. Known collectively as the UHI phenomenon, many experts say it is more pronounced in Japan than in other developed countries because of the concentration of heat-producing factors and the high humidity multiplying the effect of the rising heat. Except for the northern part of the country, such as the Hokkaido and Tohoku regions, Japanese cities often post temperatures in the mid- to high 30°C. In early August, Tokyo registered 35.8°C (96°F); Shizuoka, a prefecture near Tokyo, registered 39°C. Japan's meteorological agency said that the average temperature in Tokyo rose by 3°C over the last 100 years up to 2000; the average temperature growth for Japan's small cities was 1°C. Average temperatures for the world rose by only 0.7°C in the same period.

8.6 MITIGATION OF HEAT ISLAND EFFECTS

The UHI exists in both summer and winter seasons. In fact, it is generally largest in the winter when it has some beneficial characteristics related to reducing the demand for heating energy. In summer, however, the existence of the heat island has negative implications in three key areas—air quality, human health, and energy consumption for air conditioning. It is this summertime heat island that generally spawns an interest in mitigation. Hence, mitigation strategies are generally focused on reducing summertime heat island magnitudes and may have less desirable effects during the winter.

The primary surfaces in the urban environment that are amenable to albedo increase are rooftops, roadways, and parking lots. With respect to the plan view composition of cities, these studies typically find that roughly 20% of a city's surface is rooftop, 30% is pavement, and the remainder is a combination of vegetation canopy and other surfaces.

There are numerous examples around the world where researchers, local agencies, and governments have explored small- and large-scale implementations of heat island mitigation. In some cases, these studies are limited to computer modeling; in other cases, they involve actual modification at scales ranging from individual buildings to entire cities.

- The Heat Island Reduction Initiative (HIRI) at the US EPA supports research to advance the scientific understanding and adoption of heat island reduction strategies in US cities.
- In 1998, as part of the HIRI, the US EPA launched the UHI Pilot Project (UHIPP). Full details on UHIPP can be found at http://www.epa.gov/heatisland.
- As part of its outreach efforts, the EPA HIRI is also in the process of developing a comprehensive heat island mitigation guidebook. This guidebook will serve as a resource for communities that are interested in learning about heat island issues and developing strategies and specific measures to mitigate heat island impacts.
- The US Department of Energy was one of the early players in the field of heat island mitigation. Led by efforts within the LBNL and in cooperation

with the US EPA, the Department of Energy has developed technologies for heat island mitigation; has conducted analyses of the effectiveness of measures; and has been a leading advocate of legislation, policies, and standards that promote heat island mitigation strategies.

- Oak Ridge National Laboratory has been involved in heat island mitigation research with a focus of cool roofing technologies. They provide a wealth of information related to energy-efficient design of walls and roofs at http://www.ornl.gov/sci/roofs+walls.
- The Heat Island Research group at LBNL has been studying mitigation strategies since the late 1980s. In 1992, they published one of the first guidebooks for UHI mitigation (Akbari et al. 1992). Researchers at LBNL were among the early advocates of using highly reflective roof surfaces for UHI mitigation (Akbari et al. 1995).
- In Portland, Oregon, city planners are particularly interested in the stormwater reduction potential of green roofs. The Central City plan has a roof garden bonus, allowing new developments an extra square foot of building for each square foot of roof garden. To qualify for this bonus, the developer must cover at least half of the roof with a garden, 30% of which must be vegetation (Beckman et al. 1997).
- With respect to mitigation efforts, much of the work in Japan has focused on numerical simulation. In 2000, the city of Tokyo created a building design guidance document that encourages larger new public and private commercial developments to cover at least 20% of any flat roof area with an ecoroof.
- German cities possess by-laws that ensure that industrial buildings incorporate a green roof. Stuttgart subsidizes by up to 50% the cost of green roof installation on industrial buildings (Beckman et al. 1997). Throughout Germany, planning policies that require or encourage green roofs have had significant impact.
- The Ecover manufacturing plant in Belgium has been hailed as “the world’s first ecological factory.” It contains more than 2 ac of rooftop native grasses and wildflowers (Thompson 1998).
- The Swiss have taken an aggressive approach to green roof implementation in that they require all new buildings to relocate the green space covered by the building’s footprint at grade to the rooftop, and existing buildings, regardless of age or roof slope, to green 20% of their roofscape (Pedersen 2001).
- The city of Linz, Austria, has implemented a similar roof greening program that requires developers to compensate for any green space lost in development by covering an equivalent amount of space with greenery.

8.6.1 General Recommendations

- According to the recommendations of the EPA, planting trees and vegetation is a simple and effective way to reduce heat islands. Widespread planting in a city can decrease local surface and air temperatures. Strategic planting around homes and buildings directly cools their interiors. Shade reduces the amount of solar radiation. Studies suggest that a forest cleans the air of microparticles of all sizes 20 times better than barren land.

- Trees and other vegetation can mitigate the UHI effect because they shade buildings, intercept solar radiation, and cool the air by evapotranspiration. These islands result from storage of thermal energy in concrete, steel, and asphalt. Heat islands are 3°F–10°F warmer than the surrounding countryside. The collective effect of a large area of transpiring trees (evapotranspiration) reduces the air temperature in these areas. Trees lower air temperature through shade and increase humidity in dry climates through evaporation of moisture. Shade reduces the amount of solar radiation transmitted to underlying surfaces, keeping them cool. Shaded walls may be 9°F–36°F (5°C–20°C) cooler than the peak surface temperatures of unshaded surfaces. These cooler walls decrease the quantity of heat transmitted to buildings, thus lowering air-conditioning cooling costs. Cooler surfaces also lessen the heat island effect by reducing heat transfer to the surrounding air. A mature tree with a 30-ft. crown transpires approximately 40 gal of water per day. Evapotranspiration alone can result in peak summer temperature reductions of 2°F–9°F (1°C–5°C). While this process reduces air temperatures, it does add moisture to the air. The US Department of Agriculture Forest Service estimates that every 1% increase in canopy cover results in maximum midday air temperature reductions of 0.07°F–0.36°F (0.04°C–0.2°C). However, trees and vegetation are one factor among many that affect prevailing weather conditions.
- Urban forests are a vital component of the urban ecosystems and are gaining importance as the quality of this ecosystem is deteriorating. By cooling, trees reduce evaporative emissions from vehicles and other fuel storage, and by cooling homes and offices, trees reduce power generation emissions.
- General cooling also reduces the speed of chemical reactions that lead to the formation of ozone and particulate matter. Trees absorb CO_2 and other dangerous gases and, in turn, replenish the atmosphere with oxygen. Trees and other plants make their own food from CO_2 in the atmosphere, water, sunlight, and a small amount of soil elements. In the process, they release oxygen (O_2) for us to breathe. Trees help to settle out, trap, and hold particulate pollutants (dust, ash, pollen, and smoke) that can damage human lungs. Trees and other vegetation also can improve air quality as well as provide other amenities and aesthetic benefits such as shade and beauty. Plants also remove many toxic chemicals, such as formaldehyde and benzene, from the air and clean the soil in their root zones of toxic chemicals. In 1996, in Fort Worth, trees removed approximately 29 tons of ozone, 13 tons of sulfur dioxide, 17 tons of nitrogen dioxide, a small amount of carbon monoxide, and 592 tons of airborne particulates. Those parts of the earth's biosphere that remove pollutants from the air and store, metabolize, or transfer them are called "sinks" (Warren 1973). The soil, roots, and vegetative portions (leaves, stems, and bark) of urban forest ecosystems all function as sinks for

atmospheric pollution. In addition to the soil, vegetative surfaces, especially the leaves, remove gaseous pollution from the atmosphere (Somers 1978).

- Studies suggest that a forest cleans the air of microparticles of all sizes 20 times better than barren land. Leaves with complex shapes and large circumferences collect particles most efficiently, indicating that conifers may be more effective particle traps than deciduous species. Trees mainly absorb gases through their stomata; gases then diffuse into intercellular spaces and are absorbed by water films or react with inner leaf surfaces to form new compounds or get broken down (Smith 1990). Although some smaller particles are absorbed by leaves, most particulate matter is deposited on leaf surfaces, and, consequentially, tree surfaces are mainly temporary retainers of particulate matter (http://www.coloradotrees.org/benefits.htm).
- In 1994, trees in New York City removed an estimated 1821 t of air pollution. Air pollution removal by urban forests in New York was greater than in Atlanta (1196 t) and Baltimore (499 t), but pollution removal per square meter of canopy cover was fairly similar among these cities (New York: 13.7 g/m^2/year; Baltimore: 12.2 g/m^2/year; Atlanta: 10.6 g/m^2/year). These standardized pollution removal rates differ among cities according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables. Large, healthy trees greater than 77 cm in diameter remove approximately 70 times more air pollution annually (1.4 kg/year) than small, healthy trees less than 8 cm in diameter (0.02 kg/year). Scientists suggest that increasing tree cover from 8% to 50% in Sacramento parking lots may reduce evaporative emissions by 2%.
- In thin-screen plantation, the incoming air current can enter easily and settle the impurities inside the plantation because the wind current-carrying capacity is largely reduced. The maximum dust concentration here occurs behind the plantation, and from there, it falls steadily with the distance from the source of the dust. On the other hand, dust concentration falls rapidly inside the thicker plantation, reaching the maximum on the *luff* side and the minimum on the lee side. But, from the lee side, the concentration of dust again increases due to increased wind velocity; the lighter particles are easily carried along over the obstacle (plantation) and whorled along with the air currents.
- In thicker plantation, a fallout of dust also occurs as a side effect of turbulence but not as in thin plantation. Therefore, dense plantation has a less filtering effect compared to thin plantation. In both these plantations, the heavier particles settle down immediately on the leaf surface through impact due to gravitational force. The lighter particles (especially of a microscopic nature) are found suspended in air for a longer time because gravity does not affect them.
- Another alternative is a rooftop garden or "green roof." A green roof consists of vegetation and soil, or a growing medium, planted over a waterproof membrane.
- Green roofs also help to improve urban air quality by filtering airborne particulates and converting CO_2 into oxygen through the process of

photosynthesis. Onmura et al. (2001) conducted a field measurement on a planted roof in Japan. The evaporative cooling effect of a rooftop lawn garden showed a 50% reduction in heat flux in the rooms below the garden. This research also revealed a reduction in surface temperature from 60°C to 30°C during the day. The importance of evaporation in reducing the heat flux was quantitatively simulated in a series of wind tunnel experiments. Reviews by Wong et al. (2003) and Kohler et al. (2002) have shown that, under a green roof, indoor temperatures were found to be at least 3°C–4°C lower than outside temperatures of 25°C–30°C. In the only Canadian study, Liu and Baskaran (2003) report that field research in Ottawa has revealed that the energy required for space conditioning due to the heat flow through the green roof was reduced by more than 75%. The study focused on controlled conditions featuring a reference roof and a green roof of equal dimensions; the experimental roof surface area was 72 m^2 (800 $ft.^2$) with the green roof on one half and the reference roof on the other half. An energy reduction from 6.0 to 7.5 kWh/day for cooling was demonstrated (Bass and Baskaran 2003; Liu and Baskaran 2003).

- Green roof and vertical garden technologies can simultaneously address a number of important economic, social, and environmental challenges facing Canadian cities. They provide an outstanding number of public benefits in areas such as air-quality improvement, reduction in greenhouse gases, and storm-water quality and quantity improvements, as well as long-term economic benefits for building owners. In Europe, policy makers have established various measures to support the application of these technologies, resulting in the formation of a new green roof industry. The many public benefits attainable from green roofs and vertical gardens present a strong case for federal, provincial, and municipal government support of the proposed national action plan. Such support is fundamental to overcoming market barriers and thereby creating a viable market for such sustainable development technologies (Peck et al. 1999).
- Switching to cool paving materials is another method that could be adopted for the reduction of heat island effect. The use of cool pavements is meant to reduce pavement temperature by increasing pavement reflectivity or controlling temperature by other means, with the selected technique applied as appropriate throughout the urban area.
- Manufacturers have recently developed clean, "self-washing" white shingles with even higher SRIs—up to 62%. This is useful because the labor costs of maintaining the high albedo of a roof coating may exceed the cost of conserved energy. Reroofing with shingles rated SRI 50% or higher will keep a home cooler and reduce energy bills. Reroofing offers a quicker and even less expensive method to cool a home than planting trees, as well as making buildings and cities cooler and more comfortable.
- Porous or permeable ground surface that allows water to percolate through it can exert a cooling effect through evaporation of water in the pavement voids or from beneath (depending on the type of surface and thickness). In addition, permeable surfaces are sometimes more conducive to cooling

from convective airflow. Permeable surfaces have been used to date to control storm-water runoff; the evaporative cooling effect also could be used for heat island reduction. Both asphalt roads and concrete pavements can be built with porous surfaces, and unbound surfaces (e.g., grass, gravel) can be constructed using grids for reinforcement.

- Porous concrete helps reduce local UHI effects in several ways. Foremost, its relatively light color has a higher albedo, or reflectance, than darker pavements such as asphalt. Additionally, the pores associated with porous concrete allow it to store relatively less heat than typical concrete (Tennis et al. 2004); consequently, porous concrete absorbs less solar radiation, stores less heat, and transfers less heat to its surroundings than most paving materials. Water infiltration associated with porous concrete limits UHI effects following periods of rainfall by keeping the recesses of the pavement cool (EPA 2007). Additionally, by eliminating storm-water pooling, porous concrete dries faster and restores its surface albedo more quickly. Infiltration associated with porous concrete also provides nearby trees and plants relatively better access to oxygen and nutrients from soils beneath the pavement while reducing the temperatures near trees' upper root zones. As a result, vegetation grows faster and larger. This reduces UHI effects in the long term by providing more shade and increasing local evapotranspiration (Golden and Kaloush 2007).
- Ways to mitigate the heat island effect as well as to save energy include cool roofs, cool pavements, and vegetation.

The UHI and air-quality studies seek to observe, measure, model, and analyze how rapid growth or urban areas impact the region's climate and air quality. The site describes the UHI pilot project sponsored by the EPA and NASA, which is developing "best practices" for cities to mitigate the UHI effect. A survey of UHI research is provided to describe how heat islands develop; urban landscape and meteorological characteristics that facilitate development; use of aircraft RS data; and why heat islands are of interest to planners, elected officials, and the public.

For the first time, the Environment Ministry of Japan recognized, in its 2001 report, that warming through the heat island phenomenon was a "pollution" that must be tackled and has started field studies to determine and quantify the causes of the UHI phenomenon and to devise appropriate measures—moves that some scientists criticize as being too slow to cope with the rapidly deteriorating condition. The Tokyo Prefecture has recently introduced a regulation that imposes newly built structures to reserve 20% of roofs for green space. Last year, when the regulation took effect, 369 plans for new buildings were submitted. An official said that the number is expected to increase this year. In place of conventional asphalt, the metropolitan government has also been laying a new type of concrete block that retains moisture for road pavement.

Since 1950, rapid urbanization in major cities has made many local authorities adopt and adapt the concept of the "garden city" in Malaysia. In Singapore, the garden city is defined as a green, shady city filled with fruits and flowers—a city worthy of industrious people whose quest for progress is matched by their appreciation for the beauty of nature. Trees, flowers, and birds within a typical garden can soften the harshness of tarmac and concrete. The idea of sustainable development was applied in Singapore beginning in 1968. However, the initial step is to plant as much greenery as possible to improve the quality of the environment. The concept of a garden city became more defined and clearer only in the 1980s.

Green space has played an important role in the environmental health of urban dwellers. Implementing garden city planning will emphasize the allocation and function of green spaces for cities and towns to achieve environmental health in urban settings. Garden city planning provides sufficient open space in a network system that links residential areas to other land uses, including institutional, commercial, and recreational. The planning will ease people into interacting through circulation systems including roads, pedestrian ways, and waterways.

8.6.2 Singapore Recommendations

Through a series of studies, some general guidelines related to mitigating the UHI effect in Singapore have been generated:

- Through satellite images, the "hot" spots are normally observed on exposed hard surfaces in the urban context during the daytime. It is suggested that these exposed hard surfaces should be strategically shaded by greenery or artificial sun-shading devices.
- Historical analysis of the long-term climatic data of Singapore indicates that the rise of temperature is associated with the land uses. It is believed that implementing greening of Singapore and minimizing the release of anthropogenic heat can mitigate the UHI effect at the macrolevel.
- Temperature mapping surveys show that temperatures of the developed areas are associated with the greenery coverage within the sites. The well-planted areas have lower temperatures and locations, whereas less greenery incurs higher temperatures.
- The further exploration on the greenery indicates the positive impacts of plants on mitigating the UHI effect in Singapore. It is strongly recommended that plants can be introduced not only into a developed site as a cooling buffer but also into buildings as an insulating layer. The greenery can be introduced into the built environment in the forms of parks, rooftop gardens, and vertical landscaping.
- Through lab testing and simulations, it was indicated that the colors of building materials had significant impacts on surface temperatures, which subsequently influenced ambient temperatures. It is suggested that more light-colored materials should be employed to save cooling energy and mitigate the UHI effect.
- It was found that the heat from the asphalt road surface contributes much to the temperature increase inside the canyons. In fact, the high-rise towers randomly placed above the continuous canyons enhance the airflow and help reduce the temperature inside the canyons.
- Façade materials and especially their colors play a very important role in the formulation of the thermal environment inside urban canyons. At very low wind speeds, the effect of materials was found to be significant, and the

temperature at the middle of the narrow canyon increases significantly with the façade material having a low albedo.
- Air-conditioning condenser units spaced widely apart did not contribute much to the heat buildup inside a canyon as long as there is some wind flow. Only the immediate surroundings next to the condenser units were affected. When the condensing units were arranged vertically, a significant change was seen in the thermal environment, especially when the wind flows were perpendicular to the canyon.

The UHI effect can be counteracted slightly by using white or reflective materials to build houses, pavements, and roads, thus increasing the overall albedo of the city. This is a long-established practice in many countries. A second option is to increase the amount of well-watered vegetation. These two options can be combined with the implementation of green roofs.

8.6.3 Indian Recommendations

Experts like Mitra remind us that although mitigation can reduce the effects of climate change, it cannot halt it. Some countries have begun emphasizing the need for adaptation strategies. The New Delhi Declaration of the Eighth Conference of Parties to the UNFCC urged countries to include adaptation in their development strategies.

Sustainable building maximizes use of efficient building materials and construction practices; optimizes use of on-site sources and sinks by bioclimatic architectural practices; uses minimum energy to power itself; uses efficient equipment to meet its lighting, air conditioning, and other needs; and maximizes use of renewable sources of energy. It has been recorded that in India, wind farms can help mitigate climate change.

Mitigation efforts can be summarized as

- Reduction of energy use (per person).
- Shifting from carbon-based fossil fuels to alternative energy sources.
- Carbon capture and storage.
- Geoengineering including carbon sequestration.
- Birth control to lessen demand for resources such as energy and land clearing.
- Strategies for mitigation of global warming including development of new technologies.
- Urban planning, which includes compact community development, multiple transportation choices, mixed land uses, and practices to conserve green space. (These programs offer environmental, economic, and quality-of-life benefits and serve to reduce energy usage and greenhouse gas emissions.)
- New urbanism and transit-oriented development seek to reduce distances traveled, especially by private vehicles; encourage public transit; and make walking and cycling more attractive options.
- Building design: the possibility of using lighter-colored, more reflective materials in the development of urban areas (e.g., by painting roofs white) and planting trees.

8.6.4 Other Mitigation Strategies

Strategy	Mitigation Scenario
Urban forestry	1. Urban forestry/grass to trees (open-space planting)
	2. Urban forestry/street to trees/curbside plantings
	3. Urban forestry/grass + street to tree (open space + curbside planting)
Light surfaces	4. Light surfaces/roof to high albedo (light roofs)
	5. Light surfaces/impervious to high albedo (light surfaces)
Living roofs	6. Living roofs; roofs to grass
Ecological infrastructure	7. Urban forestry/grass + street to trees and living roofs
Urban forestry + light roofs	8. Urban forestry/grass + street to trees and light roofs
Combination of all	9. 50% open space + 50% curbside + 25% living roofs + 25% light roofs

8.6.5 Examples of Greenhouse Mitigation Options[a]

Agriculture	Reduced land conversion through improvement of farming techniques
	Improved tillage to reduce fossil fuel consumption
	Improved feed use for ruminants to reduce methane emissions
	Reduce biomass burning to reduce methane emissions
Energy supply	More efficient power generation
	Natural gas turbines in place of oil or coal use
	Gasification of fossil fuels prior to combustion
	Combined heat and power production and district heating
	Alternate energy sources: hydroelectricity, solar, nuclear, or geothermal energy
	Coal conversion technologies
Forestry	Reduced deforestation with concurrent improvement in agricultural productivity (Note: Tropical forests have the potential to sequester the largest quantity of carbon)
	Regeneration of degraded lands for reforestation
Industry	Cogeneration and steam recovery
	Efficient lighting and electric motors
	Alternate materials (e.g., replace concrete with wood)
	Use of solar power
	Heat cascading to use energy by-products of industrial processes
	Recycling of energy-intensive materials
Human settlements	Buildings with improved thermal integrity
	Condensing furnaces and heat exchanges
	Solar water heaters and insulated water storage
	Financial incentives for conservation
	Recycling
	Heat island mitigation by planting shade trees
	Utility regulations and building codes
	More efficient cook stoves

Transportation	Improved public transportation Facilitation of cycling and walking Urban traffic control for shorter transit times Car-tuning programs Improved fuel-efficient engines
Transportation	Improved energy-efficient designs of ship and aircraft Use of ethanol and methanol fuels

Source: Houghton, J. T. et al., eds., *The Science of Climate Change*, International Panel on Climate Change (IPCC), Cambridge: Cambridge University Press, 1996.

[a] Primarily carbon dioxide emission reduction unless otherwise indicated.

8.7 CONCLUSIONS AND RECOMMENDATIONS

8.7.1 Summary of Recommendations for Improving, Understanding, and Reducing Health Impacts of Climate Change

Goals	Means
Empowerment of research institutes to pursue long-term multidisciplinary research	Education campaigns for the public-health and policy-making communities about the health outcome of climate change Incentive (financial or award-oriented) for researchers and institutions to undertake multidisciplinary, collaborative research Establishment of scientifically diverse panels within key international organizations to advise on needed research areas (CGCP 1995; the current IPCC serves as a good example) Establishment of electronic networking systems for international communication and data management
Appropriate and increased research	System-based analysis of climate–ecosystem–human health relationship Use of mathematical modeling and scenario-based predictions Integration of research methods and relevant monitoring
Monitoring for early warning and quantification of health outcomes	Incorporation of relevant health indices into global observing systems (CGOS, GOOS, GTOS) Establishment of comprehensive surveillance of anticipated changes in health trends (e.g., mortality from heat waves in sentinel cities, geographic distribution of vector-borne diseases at their current margins) Linkages between present environmental monitoring and public-health monitoring Use of GISs
Preventive measures to avoid potentially adverse health outcomes, global climatic change	Precautionary action to reduce global greenhouse warming including efforts to (1) reduce greenhouse gas emissions, (2) achieve cooperation between rich and poor nations, and (3) implement sound population and development policies in the interest of both short- and long-term health benefits Primary prevention of anticipated health consequences on a regional or local level

GLOSSARY

Absorption coefficient: Measure of the amount of radiant energy incident normal to a planar surface that is absorbed per unit distance or unit mass of a substance.

Albedo: Albedo or solar reflectance is a measure of a material's ability to reflect sunlight (including visible, infrared, and ultraviolet wavelengths) on a scale of 0 to 1. An albedo value of 0.0 indicates that the surface absorbs all solar radiation, and a 1.0 albedo value represents total reflectivity.

Anthropogenic: Man-made.

Anthropogenic heat: Man-made heat generated by buildings, people, or machinery. Estimates of anthropogenic heat generation can be made by totaling all the energy used for heating and cooling, running appliances, transportation, and industrial processes. Anthropogenic heat is small in rural areas and large in dense urban areas.

Bioremediation and phytoremediation: Ability of trees and vegetation to remove pollution from rain water. Green roofs and shade trees mitigate urban runoff and nonpoint source nitrogen and phosphorus pollution through these processes.

British thermal unit (Btu): Quantity of heat required to raise the temperature of 1 lb. of water by 1°F at a specified temperature.

Canopy: The tree cover in an urban setting. Canopy size is an important determinant of a city's heat island potential. The "urban fabric" can be characterized both above and below the canopy for a better understanding of the area's surface cover.

Carbon sink: Pool (reservoir) that absorbs or takes up released carbon from another part of the carbon cycle.

Climate change: Climate change is sometimes referred to as all forms of climatic inconsistency. But because the earth's climate is never static, the term is properly used to imply a significant change from one climate to another. In some cases, climate change has been used synonymously with global warming. Scientists, however, tend to use climate change in the wider sense to include both human-induced and natural changes in climate.

Cool roofs: Term used to describe roofing material that has high solar reflectance. This characteristic can reduce heat transfer to the indoors and enhance roof durability. Cool roofs may also be highly emissive, releasing a large percentage of the solar energy that they absorb.

Deforestation: Removal of forest stands by cutting and burning to provide land for agricultural purposes, residential or industrial building sites, roads, etc., or by harvesting the trees for building materials or fuel. Oxidation of organic matter releases CO_2 to the atmosphere, and regional and global impacts may result.

Desertification: Progressive destruction or degradation of vegetative cover, especially in arid or semiarid regions bordering existing deserts. Overgrazing of rangelands, large-scale loss of forests and woodlands, drought, and burning of extensive areas all serve to destroy or degrade the land cover. The climatic impacts of this destruction include increased albedo leading to decreased precipitation, which in turn leads to less vegetative cover.

Increased atmospheric dust loading could lead to decreased monsoon rainfall and greater wind erosion and/or atmospheric pollution.

Ecosystem: Dynamic complex of plant, animal, fungus, and microorganism communities and associated nonliving environments interacting as an ecological unit.

Elastomeric roof coatings: Coatings that have elastic properties and can stretch in the summertime heat and then return to their original shape without damage. Elastomeric coatings include acrylic, silicone, and urethane materials.

Emissions: Materials (gases, particles, vapors, chemical compounds, etc.) that come out of smokestacks, chimneys, and tailpipes.

Emittance: A material's ability to release absorbed heat. Scientists use a number between 0 and 1, or 0% and 100%, to express emittance. With the exception of metals, most construction materials have emittances above 0.85 (85%).

Evapotranspiration: Process through which plants release water to the surrounding air, dissipating ambient heat. According to the US Department of Energy's Lawrence Berkeley National Laboratory, a single mature and properly watered tree with a crown of 30 ft. can "evapotranspire" up to 40 gal of water in a day. Tree planting on a large scale can reduce surrounding air temperatures.

Ethylene-propylene-diene terpolymer (EPDM): The present invention relates generally to sheeting material used for roofing. More particularly, the present invention relates to heat seamable sheeting material which exhibits improved bum resistivity. Specifically, the sheeting material comprises mineral fillers such as soft and hard clays, chemically modified clays, calcium carbonate, titanium dioxide, silicon dioxide and the like and elastomers such as ethylene-propylene-diene terpolymer, referred to herein as EPDM.

A particular application wherein EPDM are preferred because of their excellent physical properties, weathering and heat aging resistance, is in rubber sheeting, such as roofing, agricultural pond liners and water distribution membranes.

Global Climate Observing System (GCOS): GCOS was established in 1992 to ensure that the observations and information required to address climate-related issues are obtained and made available to all potential users.

Global Ocean Observing System (GOOS): GOOS is a permanent global system for observations, modeling and analysis of marine and ocean variables to support operational ocean services worldwide. GOOS provides accurate descriptions of the present state of the oceans, including living resources; continuous forecasts of the future conditions of the sea for as far ahead as possible, and the basis for forecasts of climate change.

Global Terrestrial Observing System (GTOS): GTOS is a programme for observations, modeling, and analysis of terrestrial ecosystems to support sustainable development. GTOS facilitates access to information on terrestrial ecosystems so that researchers and policy makers can detect and manage global and regional environmental change.

Global warming: Gradual rise of the earth's surface temperature. Global warming is believed to be caused by the greenhouse effect and is responsible for changes in global climate patterns and an increase in the near-surface temperature of the earth. Global warming has occurred in the distant past as the result of natural influences, but the term is most often used to refer to the warming predicted to occur as a result of increased emissions of greenhouse gases.

Greenhouse effect: Popular term used to describe the roles of water vapor, carbon dioxide, and other trace gases in keeping the earth's surface warmer than it would be otherwise. These radioactively active gases are relatively transparent to incoming shortwave radiation and relatively opaque to outgoing longwave radiation. The latter radiation, which would otherwise escape to space, is trapped by these gases within the lower levels of the atmosphere. The subsequent reradiation of some of the energy back to the surface maintains surface temperatures higher than they would be if the gases were absent. There is concern that increasing concentration of greenhouse gases, including carbon dioxide, methane, and man-made chlorofluorocarbons, may enhance the greenhouse effect and cause global warming.

Greenhouse gas: Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

Green roofs: Rooftops planted with vegetation. Intensive green roofs have thick layers of soil (6–12 in. or more) that can support a broad variety of plants or even tree species. Extensive roofs are simpler green roofs with a soil layer of 6 in. or less to support turf, grass, or other ground cover.

Heat island effect: Dome of elevated temperatures over an urban area caused by the heat absorbed by structures and pavement.

Infrared radiation: Heat energy emitted from a material. The term "infrared" refers to energy in the region of the electromagnetic radiation spectrum at wavelengths longer than those of visible light but shorter than those of radio waves.

Isotherm: Line on a chart that connects all points of equal or constant temperature.

Microclimate: Climate in a small area that varies significantly from the overall climate of a region. Microclimates are formed by natural or man-made geography and topography, such as hills, buildings, and the presence or absence of trees and vegetation.

Nitrogen oxides (NO_x): Collective term for nitrogen compounds such as NO and NO_2. These two nitrogen oxides are an environmental and public-health concern because human activity has increased their concentration in the atmosphere. NO and NO_2 are interconvertible and are precursor molecules for the production of ground-level ozone.

Ozone: Colorless gas with a pungent odor that has the molecular formula of O_3. It is found in two layers of the atmosphere: the stratosphere and the troposphere. In the stratosphere, ozone provides a protective layer shielding the earth from ultraviolet radiation's potentially harmful health effects. At the ground level (the troposphere), ozone is a pollutant that affects human health and the environment and contributes to the formation of smog.

Percolation: Movement of water downward and radially through the subsurface soil layers, usually continuing downward to the groundwater.

Pyranometer: Instrument for measuring the solar reflectance, or albedo, of materials.

Radiation: Energy emitted in the form of electromagnetic waves. Radiation has differing characteristics depending upon the wavelength.

Recharge: Process by which water is added to a reservoir or zone of saturation, often by runoff or percolation from the soil surface.

Remote sensing: Method of visualizing the radiative properties of the earth's surface using instrumentation mounted on satellites or aircraft. Remote sensing instrumentation measures the radiation reflected and emitted from the earth at different wavelengths, primarily at those wavelengths not absorbed by the atmosphere. Remotely sensed data can be converted to maps showing the visible or thermal properties of an area.

Runoff: That part of precipitation, snow melt, or irrigation water that flows from the land to streams or other surface waters.

Smog: Air pollution associated with pollutants.

Solar radiation: Heat energy from the sun, including infrared, visible, and ultraviolet wavelengths.

Solar reflectance: Measure of a surface material to reflect sunlight, including visible, infrared, and ultraviolet wavelengths, on a scale of 0–1. Solar reflectance is also called "albedo."

Solar reflective index (SRI): Composite index used by the US Green Building Council and others to estimate how hot a surface will get when exposed to full sun. The temperature of a surface depends on the surface's reflectance and emittance, as well as solar radiation. The SRI is used to determine the effect of the reflectance and emittance on the surface temperature and varies from 100, for a standard white surface, to 0 for a standard black surface. The SRI is calculated using ASTM E1980, "Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces." Materials with the highest SRI are the coolest and the most appropriate choice for mitigating the heat island effect.

Surface roughness: Used in the context of heat island mitigation to refer to the presence of buildings, trees, and other irregular land topography in an urban area.

Sustainable development: Development that meets the needs of the present without compromising the ability of the future generations to meet their own needs.

Urban fabric analysis: Method for determining the proportions of vegetative, roofed, and paved surface cover relative to the total urban surface in the city.

Urban heat island effect: Measurable increase in ambient urban air temperatures resulting primarily from the replacement of vegetation with buildings, roads, and other heat-absorbing infrastructure. The heat island effect can result in significant temperature differences between rural and urban areas.

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9 Future Sustainable City
*The Case of Masdar City**

Gajanan M. Sabnis

CONTENTS

9.1 INTRODUCTION

Masdar City was one of the most ambitious sustainable developments in the world in 2010. It aims to be one of the world's most sustainable cities. The emirate of Abu Dhabi in the United Arab Emirates (UAE) has established its leadership position by launching Masdar, a different kind of energy company. Masdar is focused on developing commercially scalable, sustainable energy solutions by working with global partners to integrate new research with proven technologies into the development of efficient systems and processes that may be replicated globally. As a result, it is contributing to the search for solutions for some of mankind's most pressing issues: energy security and climate change (Figure 9.1).

As one of Masdar's most ambitious project development business units, Masdar City seeks to become a global hub for renewable energy and clean technology, where current and future technologies will be showcased, marketed, funded, researched,

* The editor first approached Mr. Khaled Awad, from Masdar City, as an expert for this chapter. He provided all relevant information but could not complete it due to his other commitments. After the chapter was written, it was cleared for publication from Masdar City officially with useful comments. Thanks to Khaled Awad for his assistance in various ways and to Mark Bone-Knell, manager, intellectual property, Masdar City, PO Box 54115, Abu Dhabi, UAE; +971 2 653 1048; +971 2 653 3333; Fax: +971 2 653 1002; Mobile +971 50 5580295; http://www.masdarcity.com; mboneknell@masdar.ae.

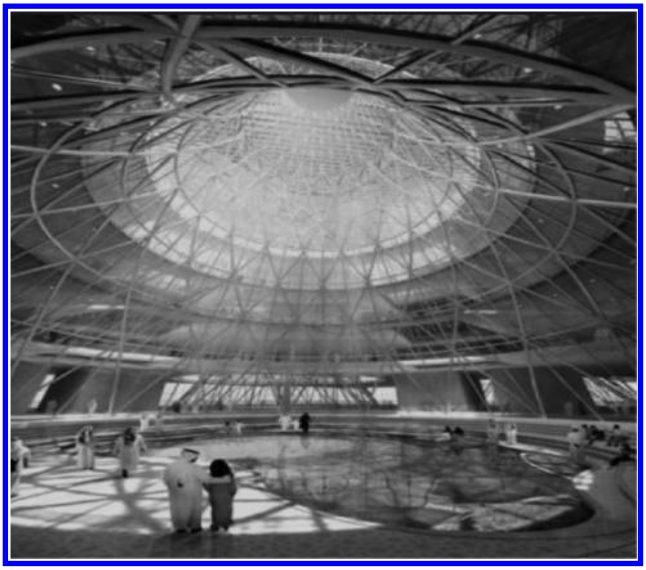

FIGURE 9.1 Masdar City perspective.

developed, tested, and implemented. Through Masdar City, Masdar will identify and share with the world the lessons learned from developing a city that meets some of the highest environmental, social, and economic goals of sustainability. As a clean-technology (clean-tech) cluster, Masdar City has already attracted some of the world's top organizations across a wide range of sectors, from smart appliances to sustainability consulting to sustainable building materials. All types of companies—from multinationals to startups—that are engaged in marketing, servicing, product demonstration, and research and development (R&D) will be a part of this journey to create, work, and live in this one-of-a-kind place.

Masdar's mission to "pursue solutions to some of mankind's most pressing issues: energy security, climate change, and truly sustainable human development"[1] will be founded with the evolution of a new-order research institute called the Masdar Institute of Science and Technology (MIST). Its structure will be based on the Massachusetts Institute of Technology (MIT) and planning calls for MIT to assist in recruitment and faculty training. A significant area of the city will be left vacant and will be made available for future technologies, such as biofuels, as they mature. Original plans execute the site plan as a raised city. This would allow for easier access for utilities and energy storage, alternate transportation, piping, and wiring, as well as flexibility for the installation of new schemas without affecting current services.

Masdar City[2] (Figure 9.2) will be built on 6 km^2 near Abu Dhabi International Airport, not far from Saadiyat and Yas Islands. Construction on the city began in 2008, and only 2 years later, during the third quarter of 2010, the first buildings to realize this vision were completed. The master-plan design meshes the centuries-old learning of traditional Arabic urban planning and architecture with leading-edge technologies to create a sustainable, high-quality living environment for all residents.

FIGURE 9.2 Location of Masdar City indicated by square near Abu Dhabi.

The city will be built in successive carefully planned and designed phases, each of which will incorporate the latest technological advances generated in its clean-tech cluster and globally, as well as Masdar City's own learning regarding development of a city that integrates the full range of sustainable technologies.

The city is strategically located at the heart of Abu Dhabi's transport infrastructure and will be linked to surrounding communities, as well as to the center of Abu Dhabi and the international airport, by a network of existing roads and new rail and public transport routes. The city will be pedestrian friendly. Because cars will be forbidden, the compact network of streets will encourage pedestrians and community social life since cars will be forbidden, while innovative transportation options will knit the city together and link it to the wider metropolis. Utility services in the city will include energy, district cooling, wet utilities (water, waste water, reused water, and storm water), telecommunication, telephony, research infrastructure, and waste management. Infrastructure support projects at the city include landscaping, common areas, leisure areas, access roads, bridges, tunnels, and information and communication technology (ICT) services, as well as development management. Masdar City is using a number of leading-edge thinkers and companies through mutually beneficial partnerships. The city is currently embarking on a global drive to attract industry partners to participate in this historic endeavor.

Masdar is a wholly owned subsidiary of the Mubadala Development Company (Mubadala), the strategic investment vehicle of the Abu Dhabi government. Abu Dhabi, with Masdar City, aims to become a world-class center of excellence and expertise, and—through MIST as well as other organizations—an R&D hub for new renewable energy and clean-tech technologies. This will not only complement Abu Dhabi's leading role in the conventional energy sector but also contribute to the emirate's strategic goal of diversifying its economy away from reliance on fossil fuels and transforming itself into a knowledge-based economy.

Thus, the goal is the establishment of an entirely new economic sector in Abu Dhabi around these new industries, which will assist economic diversification and the development of knowledge-based industries, while enhancing Abu Dhabi's existing record of environmental stewardship and its contribution to the global community. The rest of this chapter is devoted to various aspects of this historic step to shape the future of mankind.

9.2 HISTORICAL BACKGROUND[3]

In Arabic, *masdar* means "source." The company seeks to be a source on many fronts: a source of knowledge, investment capital, human capital, and innovation in the fields of renewable energy and clean technology; a source of sustainable development for Abu Dhabi and the world; and a source of solutions to help address the twin global challenges of energy security and climate change. With more than 9% of proven global oil reserves and 5% of proven gas reserves, Abu Dhabi understands the dynamics and economics of fossil fuel-based energy and has the vision to transform some of that oil wealth into a sustainable future energy resource through Masdar.

Before diving into a more detailed discussion of Masdar City, it is useful to learn more about Abu Dhabi in order to gain additional perspective. Abu Dhabi began its evolution into a modern city during the period between 1960 and 1970; today, it enjoys a very developed infrastructure much like any leading capital city. This includes wide roads, comprehensive infrastructure in water and power, and high-caliber ICT networks and services. So, in roughly 40–50 years, it has grown to be a quite modern city. But this has come at a price. Today, the UAE has one of the highest carbon footprints per capita of any country in the world and is one of the highest per-capita consumers of water, energy, and cement. In fact, it is on a par with the United States. This represents the hefty environmental price for all this growth and development.

There is the assumption that all people on the planet would like to learn and replicate Abu Dhabi's development and living style. However, unless the world moves in the direction of a Masdar City style of development, we will need several planets to sustain such a lifestyle. Abu Dhabi has achieved substantial progress in terms of infrastructure. But, in the future, the environment will be on the top of the agenda, and thus development, too, must be more sustainable.

Furthermore, the Abu Dhabi economy has always been based on oil (more than 60% of total GDP). But in the long term, this is not sustainable. Thus, Abu Dhabi has to move toward a knowledge-based economy, where knowledge, research, and innovation become the source of prosperity. Finally, Abu Dhabi does not want to remain just an importer of technology. Importing knowledge and technology from outside is not a sustainable future. Therefore, it is the right time for Abu Dhabi, using the solar potential that it has and its knowledge of and energy from its oil resource, to work toward a new beginning of a new era in this future city.

The deficiency in the current design lies in night operations. Due to the reliance on solar panels, the consumption at night will have to switch to traditional gas-fired utilities via Abu Dhabi's current grid. In the near future, this gap is due to expire through attrition via improved storage capacity and technology. Corporations and companies that use excessive amounts of energy will not be allowed to locate within the city, which will encourage local manufacturing and smaller, more efficient companies to compensate for the losses.

Thus, the mission of Masdar is a truly grand initiative; not just Masdar City but also Mubadala, as owner, is contributing to the development of the Abu Dhabi economy and reflects that the environment is a priority on Abu Dhabi's agenda for the coming decades. Masdar will contribute to making Abu Dhabi a knowledge-based economy with proper adoption of renewable energy using mainly the everlasting source of solar energy.

9.3 DEVELOPMENT OF MASDAR CITY

The Masdar City master plan was developed based on traditional Arabic city design. Despite the very harsh and hot environment in Abu Dhabi, with essentially two seasons—winter, which feels like a traditional summer in northern Europe, and hot summer—Masdar City is designed so that it is workable and livable for much more of the year than elsewhere in Abu Dhabi. A review of old cities showed that narrow streets meant buildings were closer together and thus provided shade to each other. They created neighborhoods that were mixed and multi-use places. Some of these features are seen even today in Morocco and Aleppo. One finds that these streets have their charm because of the shading and that environment of mixed use. For a clean-tech cluster, it is even better because while a person is walking, he or she is talking to another friend or even a competitor and exchanging ideas and knowledge in this environment (Figure 9.3).

Foster + Partners brought this theme into its design and developed the master plan for Masdar City. The company also has designed the previously discussed Masdar Institute campus, which is located within the city. In its design and planning, it considered the orientation of the city and the buildings to make the wind flow inside the city—to save a lot of energy just by basic passive design (and reducing the demand). *The principle of renewable energy generation* was used to get most of the required

FIGURE 9.3 Traditional Arabic design (*shibam*).

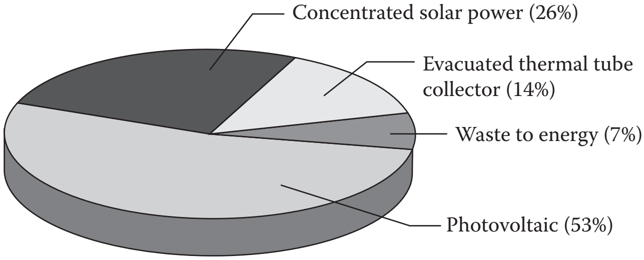

FIGURE 9.4 Sources of energy in Masdar City.

energy from photovoltaics, as well as some from solar thermal and some from evacuated thermal tubes. Even waste to energy is a possibility, and initial testing of deep subsurface geothermal energy is promising and could provide heat for thermal cooling (Figure 9.4).

9.4 CURRENT STATUS OF MASDAR CITY (2010)

Masdar City is an attempt to tie a high quality of life with a low environmental footprint. There are perhaps no other developments in the world that bring these two together. If one thinks in terms of real estate, then one has to think of how to make people happy and able to enjoy a place if one provides them with a high quality of life. One does not always think about the extent of the carbon footprint regarding that development. Masdar City is perhaps the first serious attempt to get these two things together to maximize the quality of life. If overall designs do not have to compromise on the lifestyles, it should be better and ensures that one is proud to be part of such a community.

At the same time, it makes this place a center for innovation in a different way by making a new model of the city itself as a hub of innovation and a green place for living at the same time. It will be powered partly by renewable energy, with substantially reduced waste. In short, it aims to be highly sustainable. Finally, the city will be made into a global center of excellence, with the International Renewable Energy Agency (IRENA)* contributing to making the city a center of knowledge, Think Tank leadership, and innovation. In world competition, Abu Dhabi competed for and won this hosting, which became an invaluable tool for future development. IRENA is needed for future energy crises, and it will be the vehicle taking renewable energy to different places in the world, thus increasing its adoption.[4]

* IRENA was officially established in Bonn on January 26, 2009. To date, 142 states and the European Union have signed the Statute of the Agency, among them 48 African, 37 European, 33 Asian, 15 American, and 9 Australia/Oceania states. These governments worldwide have mandated that IRENA will promote the widespread and increased adoption and sustainable use of all forms of renewable energy. Acting as the global voice for renewable energies, IRENA will facilitate access to all relevant renewable energy information, including technical data, economic data, and renewable resource potential data. IRENA will share experiences on the best practices and lessons learned regarding policy frameworks, capacity-building projects, available finance mechanisms, and renewable, energy-related energy efficiency measures.

9.4.1 Significance of Masdar City

This city is very important for people because it will provide an opportunity to participate in a project that will help define and determine the future of urban development. For the first time in history, more than 50% of the world lives in cities. This makes city development very important, and, because people are the main part of a city, social interactions are an important contributor to the quality of city life. Masdar City will be a destination for professionals and for the clean-tech world, whether one is in waste management, renewable energy, sustainable building, power storage, or water management. Therefore, it will be better to be near someone in renewable energy or waste or in carbon emission reduction and understanding corporate responsibility. This synergy in the clean-tech world is very important.

Finally, there is access to people and to leading technologies, solutions, and policies, as well as being part of the Masdar City story. This is an open source for innovation. Any good and valuable idea that is worth testing and has a clearly demonstrable possible benefit or application to the development of Masdar City can be tested here. For sponsoring companies, it is even more important because, while in the laboratory environment, they may find investors who will take the project to a different level. Eventually, the idea will become fully commercialized; an innovative idea is just the beginning. In the meantime, the product prototype is created, and the investors will be ready to provide a live platform, and this is what Masdar City will provide. This is exciting for the innovation of mankind and the future, and Masdar City is the destination.

The plan for different pilots is in progress, and many have already started. This idea of the living laboratory will continuously be an innovation hub, which is quite an interesting concept for companies such as General Electric, ABB, Siemens, BASF, etc. Many others are in the planning stage to have a presence in Masdar City. Thus, with IRENA very close, this exciting city will have different types of clean-tech value-added chains of energy, water and wastewater, green building, and energy storage.

Finally, the city is close to a market growing at a much faster pace than one thinks. The whole market growth has shifted to the East, as has innovation, with an easy access from Abu Dhabi to India and China. Masdar City will be the place where intellectual property is protected and will give the full return value to the innovator. The city has a definite growth pattern. One can see the forecast: economic growth for the next few decades. There is a clear reason to consider Masdar City as a destination, even from the business point of view.

9.5 MASDAR VISION AND VARIOUS FEATURES

Masdar consists of three project development business units: Masdar City (discussed earlier), Masdar Carbon, and Masdar Power, as well as a venture capital arm, Masdar Capital, and the independent Masdar Institute.

The *Masdar Institute* was developed in collaboration with MIT and is the world's first graduate-only institute focused on research into alternative energies and sustainable technologies as an independent, research-driven, and graduate-level program. With world-class faculty and students, it focuses its research on developing, transferring, and adapting sustainable technologies, systems, and policies to create viable energy solutions. It will be the R&D nucleus of Masdar and Masdar City. It accepted its first intake of master's degree students in September 2009, with 88 students from many parts of the world. The students enjoy a full financial package and will be the first residents of Masdar City in the university's campus housing, thereby living the sustainable lifestyle envisioned for the city (Figure 9.5).

Masdar Carbon focuses on reducing carbon emissions locally and globally through management of clean fossil-fuel power and greater industrial energy efficiency by offering technical assistance, project management, carbon financing, and emissions trading advice to high carbon producers. The unit operates a joint venture with E.ON Carbon Sourcing, called E.ON Masdar Integrated Carbon, which seeks to monetize emissions reductions resulting from improving the energy efficiency of industrial facilities. It also is developing the Abu Dhabi carbon capture and storage network in partnership with ADNOC and ADCO, which will capture CO_2 from industrial sources and reinject it into oil fields for enhanced oil recovery. Phase 1 will involve four industrial and power facilities in Abu Dhabi and capture 5 mt CO_2/year.

Masdar Power develops utility-scale renewable energy power plants around the world through direct investment in specific projects or ownership in companies manufacturing renewable energy generating equipment. Investments include the 1GW London Array, the world's largest offshore wind farm project; Torresol, a Spanish concentrated solar plant designer, developer, and operator that is a joint venture with SENER; WinWind, a Finnish wind turbine manufacturer; and Hydrogen Power Abu Dhabi, a joint venture with BP to build a 400-MW, hydrogen-fired power plant.

Masdar Capital is building with a portfolio of top-tier investments across the renewable energy and clean-tech sector, primarily through two funds; one has fully deployed its $250 million fund, and the other has made its first close of $265 million.

FIGURE 9.5 Masdar Institute under construction.

Masdar Capital seeks to generate solid returns while also pursuing portfolio investments that offer synergies with other Masdar business units. Masdar also hosts the annual World Future Energy Summit and the Zayed Future Energy Prize, which aims to inspire innovation and the development of barely imaginable solutions in the global race to address the crisis of climate change and the scarcity of sustainable energy alternatives. By creating a prize that recognizes and awards these future solutions, the Zayed Future Energy Prize hopes to inspire scientists, institutions, and energy and technology students to innovation and marketing of their ideas.

Masdar City's business model recognizes that only by collaborating with the best innovators and leading companies, universities, and others operating across a wide range of renewable energy and clean-tech fields can it achieve its sustainability goals. For companies locating in Masdar City, there are enormous benefits to locating within an environment that inspires innovation, offers business development opportunities, provides a living lab and test bed for new technologies, encourages informal knowledge sharing among like-minded professionals, and serves as a magnet for world-class clean-tech talent. The city will serve as a convenient window to tap the enormous business opportunities to be had in a number of nearby fast-growing markets within the Middle East and Asia—countries hungry for clean technology and renewable-power products and services.

Finally, Masdar City is unique in being the first clean-tech cluster to be built in what aims to be one of the most sustainable cities in the world, as well as perhaps the largest city-scale integration of the full range of renewable energy and clean-tech technologies, systems, and policies. Demand reduction is one of the most important ways in which the city will achieve its goals; this has been done through the orientation of the city and streets to maximize natural shading, by mandating high energy efficiency standards for building, and through "smart" technologies that will allow appliances and residents, workers, and students to adjust their energy use during periods of high consumption. A focus on reduce, reuse, and recycle, as well as the potential waste to energy, will seek to make a very substantial reduction in the waste sent to landfills.

9.6 PRINCIPLES FOR A LOW-CARBON MASDAR CITY

In order to achieve the city's goal of being one of the most sustainable cities in the world—as well as a great place in which to live and work—every aspect of the city's urban planning and architecture must be approached with sustainability in mind. More specifically, the design should seek to facilitate energy generation where applicable (such as the angling and shape of roofs) and reduced consumption of electricity and water. As a result, seven overriding characteristics define Masdar City:

1. Optimally oriented (previously discussed)
2. Integrated in the sense that there are no separate zones for industry, commerce, residences, leisure, etc., so that everything people need will be close at hand
3. Low-rise, high-density areas that are essential to reduce both energy demand and transportation costs
4. A vibrant urban realm in that public spaces are as important as buildings

5. Pedestrian friendly
6. High quality of life
7. Convenient public transportation

Low carbon footprint. In order to minimize the embedded carbon footprint in constructing Masdar City and its footprint from operations and maintenance, a life cycle assessment has been done on all major component materials, equipment, and systems used to construct or operate the city. This ensures, as much as possible, that the materials used to build the city are as sustainable as they can be, while the technologies, equipment, and systems that will allow the city to run are also among the most sustainable that are currently available. Because buildings represent a major portion of a city's carbon footprint, highly efficient buildings will go a long way to helping the city achieve a 70% energy reduction compared to cities of a similar size in the region. Water-saving specifications will enable a 70% reduction in potable water consumption compared to the UAE average, with separate gray- and blackwater drainage (Figure 9.6).

Waste management. The waste management strategy, in brief, is to reduce, reuse, recycle, and recover. The lifestyle within Masdar City will encourage less use of disposables in order to reduce what goes into the waste stream in the first place. Residents and office workers will separate waste at the point of disposal. Then, all waste will be sorted by the city into compostable, nonrecyclable, and recyclable waste. All appropriate biowastes will be composted, and the product will be used to enrich the landscaping. The recyclable waste will be recycled in the city or as close to the city as possible. By using this integrated system, the unnecessary use of landfill will be avoided (Figure 9.7). Masdar City has strict targets during the construction process that include the recycling of steel and other metals. Concrete is ground into rubble and reused, primarily as infill, whereas wood is stockpiled for reuse.

Integrated mobility is the most important part of transportation; however, it is not just about new technology but also about designing the city so that people can

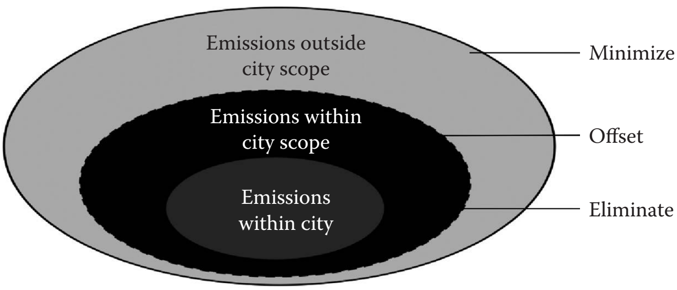

FIGURE 9.6 Net zero carbon city boundaries.

FIGURE 9.7 Waste management strategies: (a) 60% of materials recycled; (b) 30% waste to energy; (c) 10% for composting.

walk (even to work) comfortably for as much of the year as possible. As well, the city is studying a number of low-carbon transportation options, including a personal rapid transit (PRT) system being piloted by a Dutch company in the Masdar Institute buildings. It functions as a personal metro and is capable of delivery on an almost door-to-door service. The technology has already been used in Amsterdam. The system comprises automated vehicles, similar to driverless taxis, to take passengers at the touch of a button between PRT stations. The vehicles run on electricity and are guided by a computer to which they are linked by a wireless connection (Figure 9.8).

Green living is the place that people feel as livable. It is not science fiction nor an inhumane place. The idea of narrow streets, vibrant places, and high density, among other attributes, hopefully will bring charm to this place, and people should feel it as they enter Masdar City or the Masdar Institute buildings. There

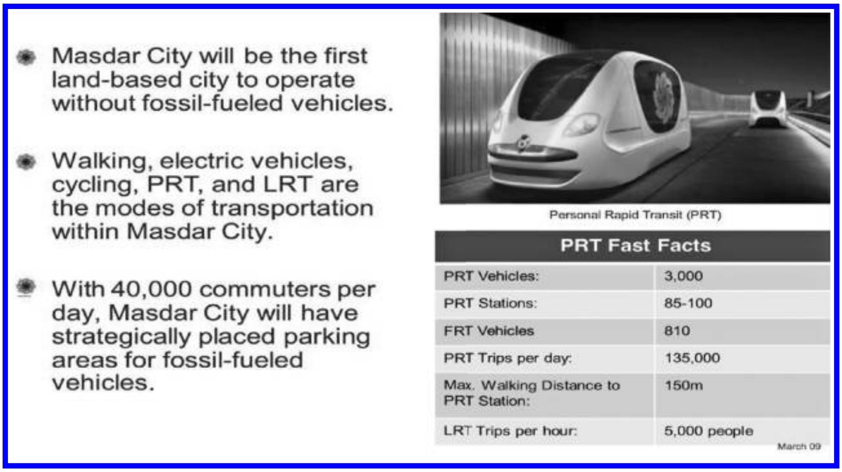

FIGURE 9.8 Integrated transportation (personal rapid transit).

is something very unique about how a city is designed. For companies operating in Masdar City, it will provide them with a highly supportive business infrastructure and environment, as well as a lifestyle that makes it a comfortable place to work. By operating in such a highly sustainable environment, these companies will be able to demonstrate their commitment to sustainable operations and practices (Figures 9.9 through 9.11).

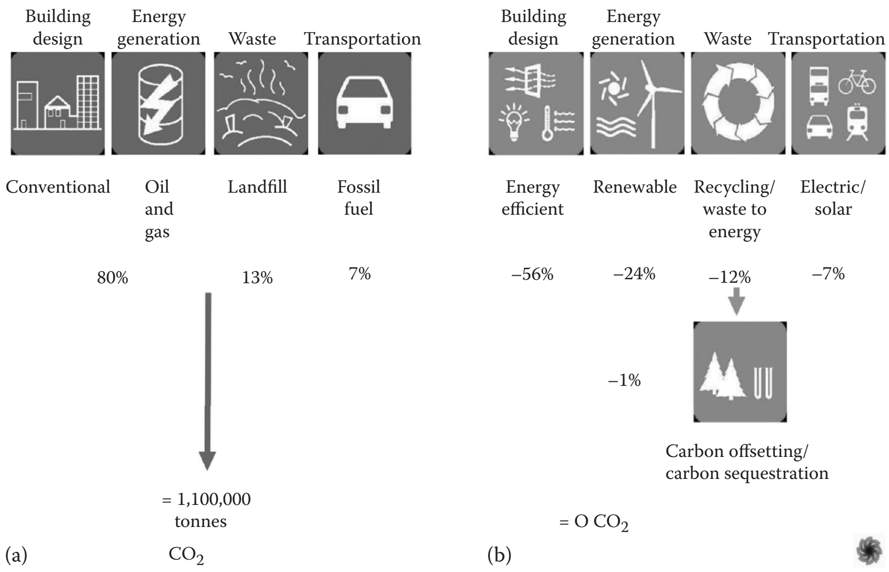

FIGURE 9.9 Conventional city (a) versus Masdar City (b).

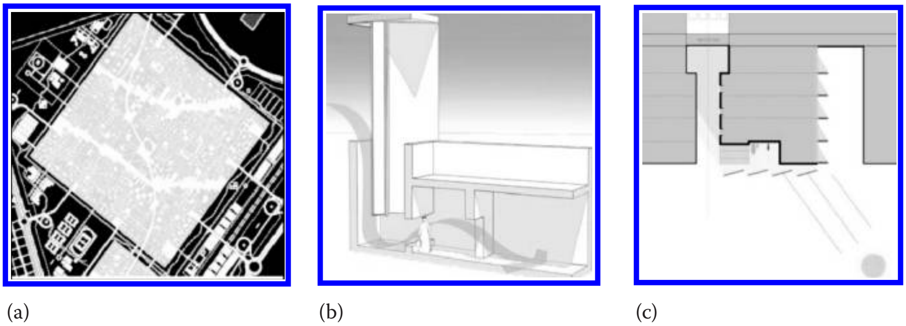

FIGURE 9.10 Passive design reduces demand: (a) NE/SW orientation; (b) natural wind towers; (c) roof day-shading.

(a) (b) (c)

FIGURE 9.11 Water-saving strategy: (a) reduce consumption to 80 L/day; (b) recycle 90% of gray water; (c) reduce water leakage to 3%.

9.7 CONCLUDING REMARKS

The Masdar City project started with the right ideas of the ideal future city. It also continued to the extent that there were ideal targets. At the time of publication of this book, only the Masdar Institute of Technology has been started—with a number of foreign students, as planned. The construction of other parts of the city, however, is not on target for dates of completion. Delivery time lines have also been extended with phase 1 scheduled for completion by 2015 and the final completion by 2020–2025. Advances in energy technology integration will now more closely follow the ongoing physical development of the city's sections.

The original ideology to engage technologists, visionaries, consultants, and investors will still form the nexus; however, the financial crisis has brought the new deliverables in step with market realities and technology priorities. It is anticipated and possibly destined for late completion. The experiment can be considered as a valuable lesson to our future generations to show how certain things can and should be done and eventually will help others to learn from this historical background. Whether Masdar City is completed on time or its vision is actually implemented, history will always give credit to one of the largest oil-producing governments, Abu Dhabi, which has one of the highest carbon footprints in the world, for inspiring humanity with a vision of future cities.

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INDUSTRY STANDARDS

Masdar's ISO Integrated Management System, Which Is Under Development

ISO 9001:2000 (ISO 9001:2008 [draft])—Quality Management Systems
ISO 14001:2004—Environmental Management Systems
OHSAS 18001:2007—Occupational Health and Safety Management Systems
EHSMS Framework: 2008—Environment, Health and Safety Management System (EHSMS) Abu Dhabi Framework Guidelines and Industry Best Practices (2008, draft)

Applicable Sustainability Standards

ISO 14020:2000—Environmental Labels and Declarations—General Principles
ISO 14021:1999—Environmental Labels and Declarations—Self-Declared Environmental Claims (Type II Environmental Labeling)
ISO 14024, 140025:2006—Environmental Labels and Declarations—Type I and III Environmental Labeling—Principles and Procedures
ISO 14040:2006—Environmental Management—Life Cycle Assessment—Principles and Framework
ISO 14044:2006—Environmental Management—Life Cycle Assessment
ISO 15392:2008—Sustainability in Building Construction—General Principles
ISO 15686-1—Building and Constructed Assets—Service Life Planning—Part 1: General Principles
ISO 15686-8—Building and Constructed Assets—Service Life Planning—Part 1: Reference Service Life and Service Life Estimation—General Principles
ISO 21929-1—Sustainability in Building Construction—Sustainability Indicators—Part 1: Framework for Development of Indicators for Buildings
ISO 21930:2007—Sustainability in Building Construction—Environmental Declaration of Building Products
ISO 21931-1—Sustainability in Building Construction—Framework for Methods of Assessment for Environmental Performance of Construction Works—Part 1: Buildings
ISO 21932—Building and Constructed Assets—Sustainability in Building Construction—Terminology

10 Sustainability and Rehabilitation of Concrete Structures

Gopal Rai

CONTENTS

10.1 INTRODUCTION

Various definitions of sustainability have been presented in earlier chapters. Its meaning in the context of rehabilitation has been integrated with the 3Rs: repair, recycle, reuse. The 3Rs classify waste management strategies according to their desirability. The waste hierarchy has taken many forms over the past decade, but the basic concept has remained the cornerstone of most strategies for minimizing wastes. The aim of the waste hierarchy is to extract the maximum practical benefits from products and to generate the minimum amount of waste and thus help sustainability.

In sustainability and the 3Rs, the problem is to identify technology or information and to determine the best and most appropriate manner in which to use it. A database on 3R technologies with a proper search engine can be created and will be useful. It must be acknowledged that the purpose of the database should be to provide information toward standardization and to improve the quality of work as related to its durability rather than to impose one-sided standards.

10.2 3RS: IMPORTANT COMPONENTS OF SUSTAINABILITY

Sustainability has become the word we use in relation to the environmental movement. But it means more than recycling, planting trees, or driving less. Sustainability encompasses three pillars or spheres: the ecological, the social, and the economic. It is a model that looks at all areas of life, the natural and the man-made, and recognizes that one cannot look at any one of these without considering the others. Sustainability and sustainable development are about developing an ecologically aware, socially just, and economically responsible society.

Western nations' dependence on nonrenewable resources has contributed to global warming and climate change, which in turn has contributed to increases in disease, poverty, and violence. Short-sighted nonrenewable resource development policies, such as the development of tar sands in northern Alberta, Canada, have led to water pollution, health problems, clear cutting, and social problems. Governments should shift their focus from unsustainable energy sources and, instead, invest in long-term, clean renewable energy sources that would not only help combat climate change but also create green jobs and build new industries.

The 3R Initiative was launched by the Office of the Prime Minister of Japan, then under the leadership of former Prime Minister Junichiro Koizumi, on June 8, 2004. As a follow-up, a conference and senior-level meetings were held in March 2006, in which the author participated. Important steps for implementation of the 3Rs were discussed. It was proposed to integrate the 3Rs with environmentally sound waste management. Also important is the integration with circular economy, sound material cycle economy, cleaner production and technologies, material flows and resource productivity, sustainable material management, zero-waste economy, waste management hierarchy, product design, life cycle assessment, sustainable production and consumption models, extended producer responsibility, green growth, green procurement, and overcoming trade barriers (taking into account the existing rules of transboundary movement of hazardous wastes). It was emphasized that commonalities clearly exist among countries at the regional level, and continued work on the 3Rs, particularly in a well-structured forum, would prove valuable. Delegates emphasized that regional cooperative efforts are one of the areas where further efforts are clearly needed.

10.3 WHAT IS REHABILITATION?

The prospects and sustained development of any nation are strongly associated with potency and consistency of the nation's infrastructure services. In the current scenario, the challenge faced by developed countries is to sustain the existing infrastructure using limited available capital.

Concrete repair is a skill that has been practiced for several centuries. Due to demand for repairs and maintenance of breakdown infrastructure, ongoing repair and rehabilitation of existing concrete structures that satisfy a variety of design and construction constraints are the challenges facing us today.

Rehabilitation of existing structures has received much attention during the past two decades. Several major research projects were launched to investigate the feasibility of using composites in both seismic and corrosion repair of structural systems made of reinforced concrete (RC), steel, and wood materials. The overwhelming experimental and analytical results have encouraged practicing civil engineers and the construction industry to consider polymer composites as an alternative construction material and system. One of the successful applications of polymer composites is the seismic repair and retrofit of RC columns. Fiber-reinforced polymer composites (FRPC) material has a number of favorable characteristics, including ease of installation, immunity to corrosion, extremely high strength, availability in convenient "to apply" forms, etc.

More than a decade ago, a new technique for strengthening structural elements emerged. The technique involves the use of FRPC as externally bonded reinforcement in critical regions of RC elements. FRPC materials, which are available today in the form of strips or in situ resin-impregnated sheets, are being used to strengthen a variety of RC elements (including beams, slabs, columns, and shear walls) to enhance the flexural, shear, and axial capacity of such elements.[2]

Because composites are very promising materials in repair and rehabilitation, they are increasingly used worldwide. In Japan, the driving interest appears to be in construction materials and methods that enhance prefabrication, automation, labor savings, and, in general, cleaner, more efficient construction processes. In North America, the major interest is to find a solution to the durability problem caused by steel reinforcement corrosion in infrastructure. Europe may have a combination of all of the above coupled with a keen interest in strengthening/rehabilitation as a result of its large number of invaluable historical structures in need of repair.[3,4]

10.4 MOTIVATION OF WORK

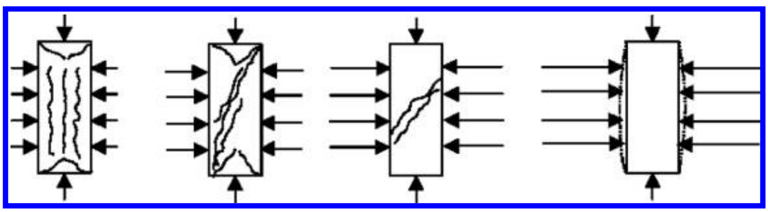
Rehabilitation and retrofits of RC-framed structures are a big concern of the present construction community. The typical lacuna in the present structure is improper detailing of reinforcements at the joints that leads to their brittle failure. The use of RC jackets and steel plate jackets to strengthen the joints has been reported earlier. However, execution of such rehabilitation is disruptive to the operation of the facility, labor intensive, and very time consuming. The FRPC material has promise in alleviating these difficulties. The efficiency of FRPC as a device for enhancement of bending and shear capacities of flexure elements and enhancement of confinement of concrete in compression elements has been well established.

This chapter describes the importance of composite materials in axial and flexural rehabilitation works in comparison with the conventional rehabilitation methodology and case studies in the Indian environment, as well as the preliminary design concept with working methodology.

10.4.1 Concept of Axial Strengthening by Confinement

Concrete is relatively weak in tension and strong in compression. The concrete tensile strength is of the order of one-tenth that of the compressive strength. A typical Poisson ratio value for concrete is 0.20. Thus, it is often argued that concrete always fails in tension. However, if the lateral extension of concrete is restricted by external confining pressure, it can withstand higher axial stress. As shown in Figure 10.1, under low confining stress, concrete cylinders fail by crushing of the concrete, sometimes along with splitting tension cracks parallel to the direction of the applied load. A single major shear crack is formed at failure for an intermediate level of confinement. Under high confining stress, no major cracks form, and inelastic deformation is distributed within the concrete specimen. In any event, the strength and deformability of a concrete cylinder increase as confining stress increases.

By confining the concrete with a continuous fiber-reinforced polymer (FRP) jacket, the fibers resist the transverse expansion of the concrete. This resistance provides a confining pressure to the concrete. At low levels of longitudinal stress, the transverse strains are so low that the wrap induces little confinement. However, at longitudinal stress levels above the critical stress, the dramatic increase in transverse strains engages the FRP jacket, and the confining pressure becomes significant. The



(a) (b) (c) (d)

FIGURE 10.1 Failure modes of concrete cylinders under various confining stresses: (a) 100 psi; (b) 500 psi: (c) 1000 psi; (d) 2000 psi.

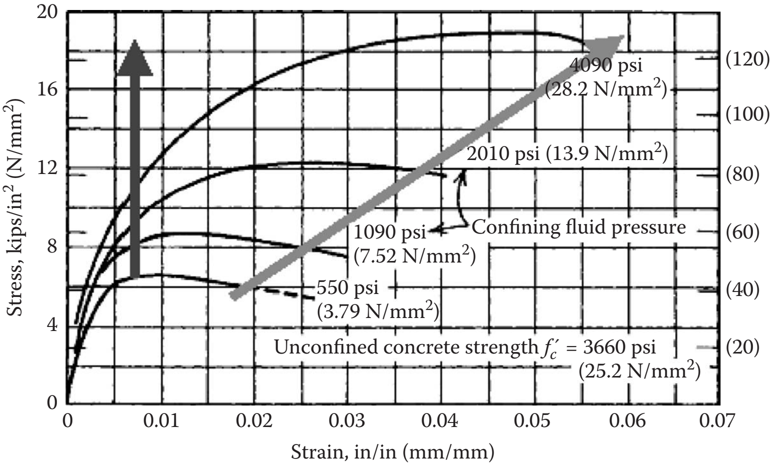


FIGURE 10.2 Stress–strain curves for concrete cylinders under different confining stress. (From Mukherjee, A., and G. L. Rai. *Construction & Building Materials* 23: 822–828, 2009.)

effect of the confining pressure is to induce a triaxial state of stress in the concrete. It is well understood that concrete under triaxial compressive stress exhibits superior behavior in both strength and ductility compared to that of concrete in uniaxial compression. Typical experimental stress–strain curves for concrete cylinders under different confining stress are given in Figure 10.2.[5]

10.4.2 Stress–Strain Relationship for Confined Concrete

Apparently, the most widely accepted stress–strain relationship for confined concrete is that proposed by Mander (Figure 10.3), which was originally developed for confinement by steel hoops. The American Concrete Institute (ACI) 440.2R-02,[6]

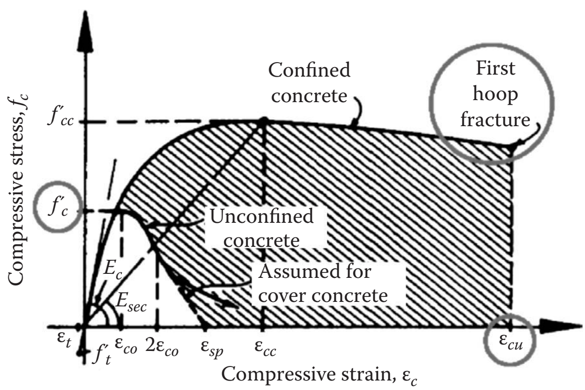


FIGURE 10.3 Stress–strain relationship for confined concrete. (From Mukherjee, A., S. P. Bagadi, and G. L. Rai. *Journal of Composites for Construction* 13 (2): 74–81, 2009.)

EuroCode 8 part 3,[7] and CEB-FIP bulletin 14[8] also recommend that the same relationship be used for FRP confined concrete.

The shaded area in the stress–strain relationship of Figure 10.3[9] characterizes the additional energy that can be absorbed in a confined section. The Mander model is applicable to all section shapes and all levels of confinement.

The cylinder strength of the confined concrete, f_{cc}, which is generally taken as 0.8 times the cubed strength of the confined concrete, is given by

$$f_{cc} = f_c\left(2.254\sqrt{\left(1+7.94f_l/f_c\right)} - 2f_l/f_c - 1.254\right) \qquad (10.1)$$

where

- f_c is the cylinder strength of unconfined concrete = $0.8f_{\text{ck}}$;
- f_{cc} is the cylinder strength of confined concrete; and
- f_l is the confining stress.

The confining stress depends on the thickness, strength, and spacing of the confining reinforcement wrapping.

In Equation 10.1, the peak confined cylinder strength, f_{cc}, is a function of the effective lateral confining pressure f_l. With $f_l = 0$, $f_{cc} = f_c$ (peak unconfined cylinder strength).

10.5 CONFINEMENT BY FRP WRAPPING

As mentioned earlier, by wrapping the concrete with a continuous FRP jacket (Figure 10.4), the fibers resist the transverse expansion of the concrete. This resistance provides a confining pressure to the concrete. The improvement to the behavior of concrete is quantified based on the observation that concrete wrapped with an FRP jacket exhibits a bilinear stress–strain response. Initially, the stress–strain behavior is unchanged from that of unconfined concrete. However, beyond the peak stress for unconfined concrete, the stress level in confined concrete continues to increase with

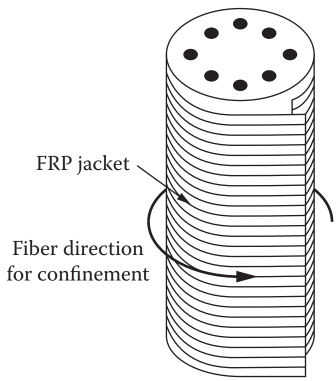


FIGURE 10.4 FRP wrapping of concrete column.

increasing strain. The rate of increase is roughly proportional to the stiffness of the confining jacket.

To quantify the behavior of concrete encased by an FRP jacket, it is necessary to determine the amount of confining pressure that the FRP jacket supplies. The confining pressure is a function of the stiffness of the jacket and the transverse expansion of the concrete. By strain compatibility, the strain in the jacket is equal to the transverse strain in the concrete. The confining pressure may then be found by analyzing the statics of a thin-walled cylindrical cylinder (Figure 10.5).

This analysis yields the confining pressure $f_{cp} = f_l$, as given by

$$f_{cp} = f_f \rho_f / 2 \tag{10.2}$$

where

$$\rho_f = 4t_j / h \tag{10.3}$$

The apparent increase in the compressive strength of concrete under the confining pressure supplied by the jacket is again quantified by Equation 10.1.

For rectangular section, confining stresses in two directions are different. Therefore, f_l is a function of f_{lx} and f_{ly} and is to be determined from Figure 10.6. The effective confining stresses in two directions are given by

$$f_{lx} = k_e f_{lx} \tag{10.4}$$

$$f_{ly} = k_e f_{ly} \tag{10.5}$$

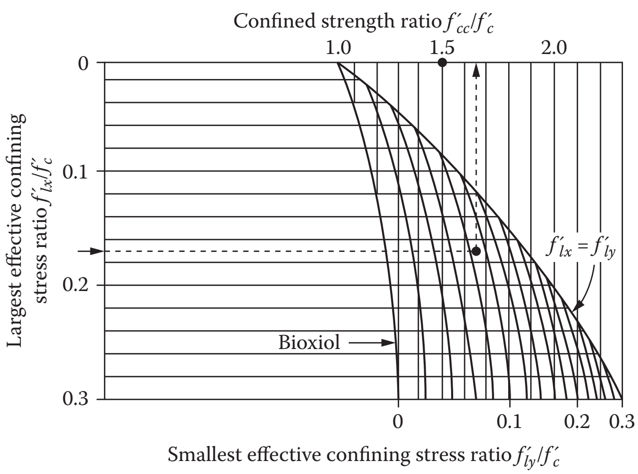


FIGURE 10.5 Confined strength ratio for rectangular sections.

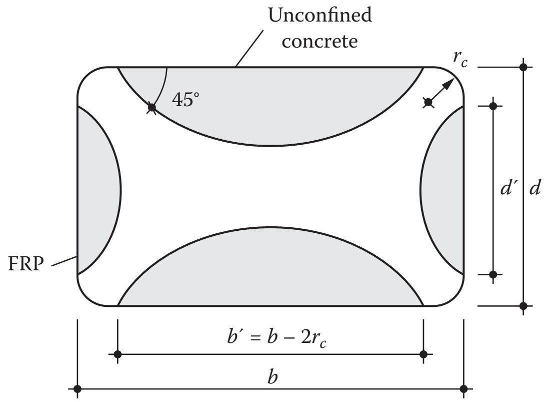


FIGURE 10.6 Effective confined area in a rectangular column.

For continuous fiber wrap,

$$f_{lx} = 2f_f t_j / b' \tag{10.6}$$

$$f_{ly} = 2f_f t_j / d' \tag{10.7}$$

k_e is the effectiveness coefficient given by

$$k_e = 1 - (b'^2 + d'^2)/3bd \tag{10.8}$$

where

$$b' = b - 2r_c \tag{10.9}$$

$$d' = d - 2r_c \tag{10.10}$$

r_c is the rounding-off radius, which is introduced to prevent the high stress concentration and tear-off of wrap at sharp edges (Figure 10.6).

10.5.1 Advantages of FRP Wrapping over Other Methods

FRP wrapping has got several advantages over conventional methods of strengthening. A few of them are listed here:

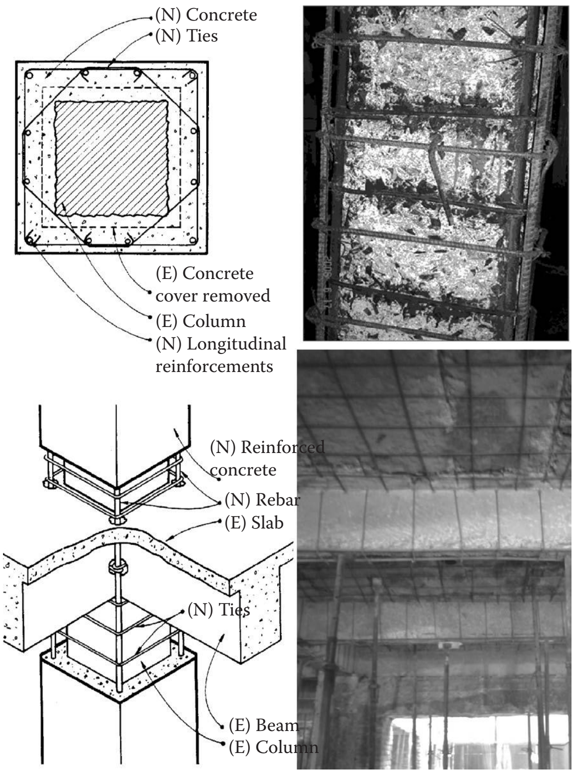
- It provides a highly effective confinement to columns.
- The original size, shape, and weight of the members are practically unaltered.
- Due to the orthotropy built in by the fiber orientation, the wraps essentially provide confinement only, without interfering with the axial load, which is taken completely by concrete column.
- No drilling of holes is required.

- The use of FRP for strengthening has become attractive because of its easiness and the speed of application due to its lightweight and minimal thickness requirement and due to its high strength.
- FRPs have extremely good corrosion resistance, which makes them highly suitable for marine and coastal environments.
- The wraps are available in long rolls, so construction joints can be easily avoided.

10.6 STRENGTHENING TECHNIQUES FOR RC COLUMNS OTHER THAN FRP WRAPPING

10.6.1 Concrete Jacketing

- Involves addition of a thick layer of RC in the form of a jacket using longitudinal reinforcement and transverse ties.
- Additional concrete and reinforcement contribute to strength increase.
- Minimum allowable thickness of jacket = 100 mm.
- The sizes of the sections are increased, and the free available usable space becomes less.
- Huge dead mass is added.
- The stiffness of the system is greatly increased.



- Requires adequate dowelling to the existing column.
- Longitudinal bars need to be anchored to the foundation and should be continuous through the slab.
- Requires drilling of holes in existing column, slab, beams, and footings.
- Increase in size, weight, and stiffness of the column.
- Placement of ties in beam column joints is not practically feasible.
- The speed of implementation is slow.

10.6.2 Steel Jacketing

- The column is encased with steel plates, and the gap is filled with a non-shrink grout.
- This provides passive confinement to core concrete.

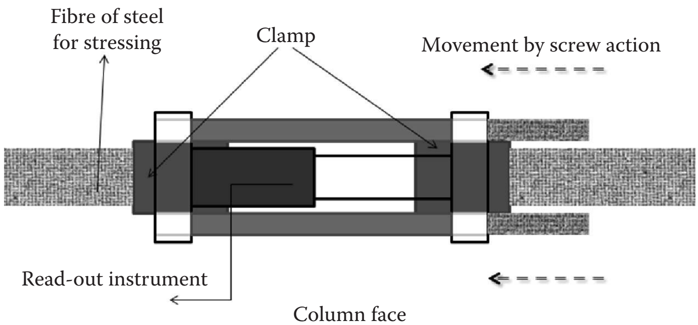
- Its resistance in axial and hoop direction can be neither uncoupled nor optimized.
- Its high Young's modulus causes the steel to take a large portion of the axial load, resulting sometimes in premature buckling of the steel.
- General thickness of grout = 25 mm.
- Rectangular steel jackets on rectangular columns are not generally recommended, and use of an elliptical jacket is recommended.
- Since the steel jacket is vulnerable to corrosion and impact from floating materials, it is not used for columns in rivers, lakes, and seas.

10.6.3 Precast Concrete Jacketing

- This helps to speed up construction.
- New longitudinal reinforcement is set around the existing column, and precast concrete segments are set around the new reinforcement.
- All segments are tied together by strands.
- After injecting nonshrinkage mortar between the existing concrete and precast concrete segment, prestressed force is introduced in the strands to ensure the contact of the segments.

10.6.4 External Prestressing

- This involves prestressing the columns with external strands to provide active confinement.
- It is efficient and can be more economical than steel jacketing.



- Installation of such a system can be less disturbing to building occupants.
- The technique is newly developed, and on-site implementation is not known.
- Shear strength increase is only due to increase in concrete strength against the jacketing, where the jacket contributes significantly toward shear strength.

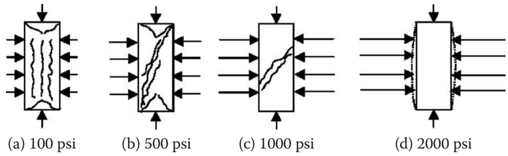
10.7 STRENGTHENING OF RC COLUMNS BY FRP COMPOSITES

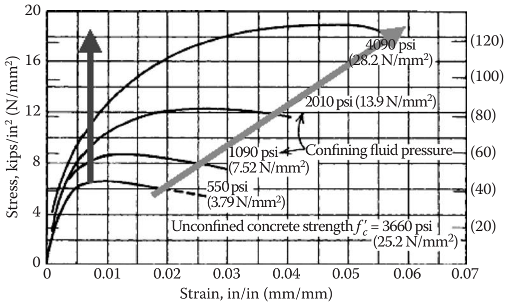
- This involves wrapping of RC columns by high-strength, low-weight fiber wraps to provide passive confinement, which increases both strength and ductility.
- FRP sheets are wrapped around the columns, with fibers oriented perpendicularly to the longitudinal axis of the column, and are fixed to the column using epoxy resin.
- The wrap not only provides passive confinement and increases the concrete strength but also builds up significant strength against shear.

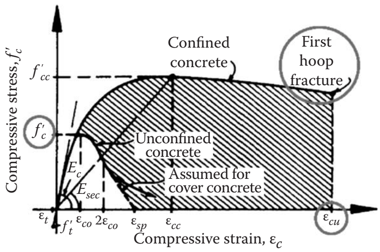
10.7.1 Advantages of FRPs for Strengthening RC Columns

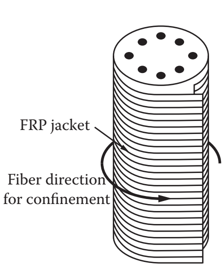
- It provides a highly effective confinement to columns.

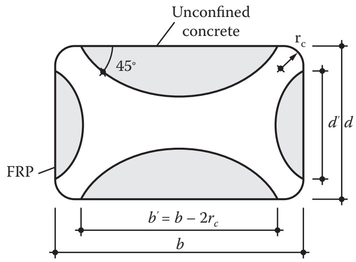
- The original size, shape, and weight of the members are unaltered (unlike any other jacketing), and they thus do not attract higher seismic forces.
- Because the original shape and size of the members are practically unaltered, this method is particularly useful for strengthening historic and artistic masonry structures.
- Due to the orthotropy built in by fiber orientation, the wraps essentially provide only confinement, without interfering with the axial load, which is borne completely by the concrete column, unlike steel jacketing, where the jacket takes on most of the axial load and becomes susceptible to buckling.











- No drilling of holes is required in contrast to concrete and steel jacketing.
- FRPs have extremely good corrosion resistance, which makes them highly suitable for marine and coastal environments.FRP wraps prevent further deterioration of concrete and inside reinforcement.
- The wraps are available in long rolls, so construction joints can be easily avoided.
- Ease of installation, similar to putting up wallpaper, makes the use of FRP sheets a very cost-effective and efficient alternative in the strengthening of existing buildings.
- FRP provides minimal disturbance to existing structure, and the strengthening work can generally be performed with normal functioning of the structure.

10.8 CONCEPT OF CONFINEMENT[10]

- As concrete is uniaxially compressed, Poisson's effect induces transverse strains that result in radial expansion of the concrete.
- This increase in transverse strain results in volumetric expansion.
- By confining the concrete using a continuous FRP jacket, the fibers resist the transverse expansion of the concrete.

- The confining pressure provided by wrap induces a triaxial state of stress in the concrete, which thus exhibits behavior in both strength and ductility superior to those of concrete under uniaxial compression.
- Since the FRP jacket acts to contain damaged sections of concrete, the maximum usable strain level in the concrete is limited only by the ultimate strain obtainable in the FRP jacket rather than by concrete crushing.
- To increase the effectiveness of wrap, the sharp edges of the rectangular sections must be rounded.

10.9 DESIGN OF FRP STRENGTHENING

The design of FRP strengthening follows the well-established principles of mechanics. Most major codes, like ACI, CEB-FIP, EuroCode, Japanese code, Swedish Bridge Code, Chinese standard, Turkish code, etc., give guidelines for the design of an FRP system for wrapping of concrete columns to increase their capacity. Various institutes, like NCHRP, Caltrans, CPWD, etc., recommend the use of FRP composites for strengthening of concrete structures.

For design of strengthening, a composite action is assumed between fiber and existing concrete. The design is based on the following assumptions:

- There is no slip between FRP and concrete.
- Shear deformation within the adhesive layer is neglected.
- Tensile strength of concrete is neglected.
- The FRP jacket has a linear elastic stress–strain relationship up to failure.

10.10 CORROSION PROTECTION BY FRP

- Corrosion in RC structures causes deterioration of infrastructure.
- Structures in or near marine environments are especially vulnerable.
- A widely promoted method for protecting structures in corrosive environments is the application of FRP composite wraps over the surface of the concrete elements.
- Corrosion due to chloride ingress is purportedly arrested by the prevention of further chloride contamination and penetration by the oxygen and water needed to continue a corrosion process that has begun or has caused damage.

A design example following this process is presented in the Appendix.

10.11 ON-SITE APPLICATION OF FRP WRAPPING

A proper application procedure involves the following steps:

1. Surface preparation, which includes
    - Grinding to remove the loose cement particle from the column surface
    - Repair of hairline cracks, if any

Grinding the concrete surface

Repair of hairline cracks

- Rounding off of column corners to the specified rounding radius
- Application of primer

2. Once the surface is prepared and the primer is dried, the next step is application of saturant:
   - The fiber is wetted with saturant.

Application of saturant

Wetting of wrap with saturant

- The fiber is then wrapped on the column skillfully so that there are no undulations in the wrap.

Wrapping with carbon fiber

Wrapping with glass fiber

- After wrapping, the fiber is again wetted with one more layer of saturant to make sure that the fiber is soaked fully.

Application of saturant on FRP wrapping

Description	Concrete Jacketing	Steel Jacketing	FRP Wrapping	Remarks
Mode of strengthening	Increase in concrete and steel area	Confinement	Confinement	_
Preparation of column for strengthening	Significant dismantling of cover concrete; at least 40 mm cover concrete to be removed; epoxy primer to be applied on exposed surface	No major dismantling work involved; mainly plaster to be removed and epoxy primer to be applied on exposed surface	Only plaster to be removed and epoxy primer to be applied on exposed surface; for rectangular columns, corners to be rounded off	FRP involves minimum surface preparation
Drilling of holes	Large amount of drilling required	Large amount of drilling required	No drilling required	FRP involves minimum work since no drilling is required
Additional weight	Extremely high (in the example shown, the weight becomes 225% for just 50% increase in strength)	Very high (in the example shown, the weight becomes 169% for 50% increase in strength)	Negligible; no increase in weight at all	FRP does not increase the dead weight of the structure
Size increase	Very high (in the example shown, the diameter of the column increases from 400 to 600 mm for 50% increase in strength)	High (in the example shown, the diameter of the column increases from 400 to 450 mm for 50% increase in strength)	Negligible; the total increase in the diameter is less than 5 mm	The size remains unaltered, thus retaining the free area

10.11.1 Flexural Enhancement

The efficacy of FRC in improving confinement of concrete and thus improving its performance in extreme loading is well established.[11] FRC has also been effective in augmenting the reinforcement in flexural members.[12] The seismic performance of RC frame structures can also be dramatically improved by externally bonding FRC at the beam–column joints.[13] The advantages of resistance to corrosion and higher specific strength make these materials ideal for reinforcing existing structures with minimum intrusion. The popular method adopted in such cases is adhesively bonding FRC on concrete structures. However, the superior strength of FRC can seldom be fully utilized due to poor capacities of the concrete and the interfaces.

Prestressing of concrete has been an effective method in exploiting its relatively higher compression capacity. Moreover, the permanent deformations in the structure can be recovered by prestressing. Although the technique is well established in new structures, external prestressing of existing structures has always been difficult, especially in view of reinforcement corrosion, lateral instability, end anchorages, and space restrictions. In this chapter, we explore an external prestressing technology with FRC that alleviates all these problems. We also address concerns such as substrate failure, edge peeling, stress relaxation, and durability.

Prior research on some aspects of prestressed FRC is available. Triantafillou and Deskovic[14] determined the limiting prestress levels to avoid edge peeling, and Triantafillou et al.[15] provided limited experimental verification of their analytical work. However, this limit can be exceeded if the concrete in the edge zone is reinforced in tension. It was concluded that FRC prestressed concrete members exhibit excellent strength, stiffness, and ductility characteristics, as long as the external reinforcement is adequately anchored at its ends. Sadaatmanesh and Ehsani[16] provided prestress to RC beams by cambering them with hydraulic jacks, while the composite plate was bonded and cured. The authors reported that this resulted in improved cracking behavior. El-Hacha[17] strengthened precracked RC beams with carbon FRC (CFRC) sheets and investigated the effect of temperature on them. He concluded that beams strengthened at low temperature failed at higher loads than those at room temperature. Quantrill et al.[18] studied flexural strengthening of RC beams externally prestressed with CFRC laminates using a mechanical anchorage system.

The key issues on this topic are safe levels of prestress, anchorage system, application methods, durability, and modeling and design methods. In this chapter, we address some of these issues. RC beams that have been loaded to failure have been restored with CFRC laminates that are prestressed at different levels. A method of anchorage of the laminates has been investigated. An experimental program on long-term performance of the prestressed beams has been described, and intermediate results have been reported.

10.11.2 Prestressing System

1. Surface preparation is the basic treatment necessary before any application process. For this purpose, the surface is thoroughly cleaned using a grinder; it is important for strong bonding between concrete and laminate.

2. Marking for plate and machine area. Marking should be precise and free from even small approximations; otherwise, it can cause damage to laminate and machinery. Meanwhile, the cleaned area is also applied with primer to further smooth the surface.

3. The end plates (i.e., anchor plates, which are used to avoid the prestressed laminates peeling off from the ends when kept in a perpetually stressed position) are fastened to the concrete surface with the help of heavy-duty anchor bolts, which are bolted in after drilling sufficiently deeply into concrete and being aligned properly.

4. Behind the anchor plate, a clamping device on both sides, with supporting L-clamps, is present; it holds the laminate with the help of high-tension bolts (Figure 10.7).
5. The laminate is cut to the required length so that it can be clamped in the clamping devices at both ends.

FIGURE 10.7 Positioning of laminate clamping device between L-clamps.

6. The laminate is now fixed, with adhesive applied along its length, and the piston body is put into position, after which the clamping device is pushed back to achieve the required design load (Figure 10.8).
7. After the final setting of adhesive, the mobile anchorage (clamping device and L-clamps) is removed, and excess laminate length is cut off (Figures 10.9 and 10.10).

Many times, to provide more strength against peeling, laminates are further secured at the ends by means of a CFRC sheet. The fiber wraps are aligned 90° to the longitudinal axis of the member.

The first repair work of a concrete bridge using these CFRC laminates was carried out at IBach Bridge, Lucerne, Switzerland. The bridge, with a 228-m span, was

FIGURE 10.8 Fixing of laminate with adhesive in the machine. The pump for giving pressure is attached.

FIGURE 10.9 The final look of the slab after fixing all the prestressed laminates.

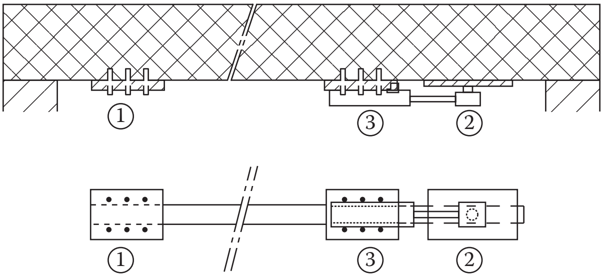


FIGURE 10.10 Prestressing system: (1) fixed anchor; (2) mobile anchor; (3) prestressing system. Many times, to provide more strength to avoid peeling, laminates are further secured at the ends by means of a CFRC sheet. The fiber wraps are aligned 90° to the longitudinal axis of the member.

designed as a continuous beam with a 39-m span. Prestressing tendons prevented the bridge from operating at full capacity, hence further improving the strength. The bridge was repaired with 2 × 150-mm CFRC laminates. The major observations noted were as follows:

- Due to its very low weight, 175 kg of steel was repaired with just 6.2 kg of CFRC.
- Hence, use of scaffolding was avoided, and the whole project was carried out with hydraulic lift alone.
- Composites were positioned and held with the help of vacuum bags, thus avoiding big closets for steel plates.
- Even though CFRC laminate was 40 times more expensive than steel plates, it saved 20% cost due to ease in execution of the project.

For effective bonding of concrete and the strengthening element, Sadaatmanesh and Ehsani[16] found that epoxies should have sufficient stiffness and strength to transfer the shear force between the composite plate and concrete. They should also prevent brittle bond failure as a result of cracking of concrete. Thus, they recommended the use of epoxies with toughened rubber for this purpose.

Prestressing has many observed advantages because it increases the effective usage of composite properties:

- Prestressing is effective in closing cracks in damaged structures and thus increasing the life of the structure.
- Also, prestressing reduces the stress developed in the structural members' reinforcing steel by giving a back force to the structure. This is useful when the rebars are weakened due to corrosion.
- Another significant advantage of prestressing is that it reduces the tendency of delamination at the crack front.

10.12 FUTURE OPPORTUNITIES FOR REHABILITATION AND REPAIR OF CONCRETE STRUCTURES

The future of the concrete repair industry appears to be promising and bright, judging from the projections based on current trends in repair, rehabilitation, restoration, and strengthening of existing infrastructure. However, this optimism must be tempered in light of the need to change the image of the industry from one that is often self-serving—the industry that is repairing the repairs. Due to the increasing public concern about durability of concrete structures in general and repaired concrete structures in particular, the subject of steel corrosion and corrosion protection in repaired concrete structures is discussed with reference to the deficiencies in our knowledge of corrosion and corrosion protection in concrete repair, methods of testing, and the science of repair durability.[19]

The concrete repair, protection, and strengthening industry is driven by the defects of, damage to, and deterioration in concrete structures along with changes in use and code requirements. Over 500 million $yd.^3$ of concrete are placed every year in the United States. Much of the concrete is custom made for almost every job, using local materials of varying quality, some designs that are not standard, and accelerated construction processes that sometimes sacrifice quality in the interest of meeting a schedule. The annual cost to owners for repair, protection, and strengthening is estimated at $18 billion to $21 billion in the United States. The result is the industry of "rehabilitation" that supports engineers, architects, equipment suppliers, material manufacturers, researchers, educators, testing companies, and contractors.[19]

Among the global forces that are shaping the repair and restoration industry are a shift in the manner that scientific research is carried out on the deterioration process and the evaluation of repair materials. The compatibility of these materials in repair systems, the emphasis on the environmental safety aspects of materials, and the increased need for performance specifications are the main considerations.

The process of degradation that affects durability is very complex. Each is nonlinear and often irregular and interacts physically, chemically, and sometimes biologically with other processes and the environment. As a result, simple solutions addressing each process in isolation are inadequate. A holistic approach that provides an understanding of a phenomenon or a structure in terms of an integrated whole is required. A holistic model for deterioration takes into account the effect of both the scientific facts and the experimental knowledge of environmental factors and how they affect each component of the structure. The model suggests that, to achieve durable repairs, it is necessary to consider the factors affecting the design and selection of repair systems as parts of a whole or as components of a composite system.

10.12.1 Cost of Repair, Protection, and Strengthening of Concrete in the United States

The United States consumes over 100 million t of cement annually, with a large portion used for the production of concrete. It is estimated that over 500 million $yd.^3$ of concrete (almost 2 yd. person) is installed each year to support the US infrastructure.

The volume of in-place concrete is estimated at 9 billion yd (32 yd. person). Most of this concrete is older than 20 years. Sometimes exposed to freezing–thaw cycles, carbonation, chlorides, and other aggressive chemicals, concrete can have a useful life of 50 years or longer. More recent developments in the use of low-permeability concrete mixtures, proper use of air entrainment, epoxy-coated reinforcement, protective coatings, and corrosion-reducing admixtures have greatly increased the service life of concrete structures beyond 30 years.

However, some concrete structures being built today may require repairs after as few as 5 years of service. The original design and construction of these structures did not take advantage of these technologies, instead often emphasizing low first cost. More efficient designs may be less tolerant of workmanship and design errors, and fast-track construction methods may make it more difficult to incorporate the quality needed for a long service life. As a result, some new structures, in spite of durability enhancements, undergo early-age deterioration and require repair. Likewise, repairs intended to extend the service life of structures often fail prematurely due to the improper use of repair materials.

It is estimated that the total cost for repair, rehabilitation, strengthening, and protection (including waterproofing) of the concrete structures in the United States is \$18 billion to \$21 billion a year. Assuming that there is 9 billion yd.^{3} of concrete in these structures, the annual cost is between \$2.00/yd.^{3} and \$2.33/yd.^{3} of in-place concrete.

10.12.2 Unified Approach to Sustainability and Rehabilitation[20]

In 2004, concrete repair industry leaders came together to develop an industry-wide strategic plan (Vision 2020). The Strategic Development Council (SDC), an inter-industry development group dedicated to supporting the concrete industry's strategic needs, facilitated Vision 2020 at the request of the concrete repair and protection industry. The purpose of Vision 2020 was to establish a set of goals to improve the efficiency, safety, and quality of concrete repair and protection activities. By focusing on the most important industry goals, it is hoped that the repair industry will achieve these goals faster than if the industry is left to evolve on its own. The focus on goals for repair is also related to the major issue of sustainability because extending the useful life of existing installations is a key factor in producing a sustainable environment. Over 100 industry leaders, including contractors, engineers, material manufacturers, researchers, educators, owners, and industry association executives, participated in focused workshops to define the most important industry issues and needs used to establish the goals in Vision 2020.

A vision provides a glimpse of the future state of the industry. If most key people in the repair industry believe that no improvements are necessary and that there are no significant problems to solve, their vision will result in a future state of the industry that is no different from what we see today. Repair industry leaders have spoken in the Vision 2020 workshops, and they envision a great need for improvement. These improvements include reducing mistakes during repair, miscalculations, and poor workmanship and performance as well as finding better repair methodologies that reduce costs while improving quality. This vision and the goals related to achieving it are the basis for moving forward and helping industry organizations, research establishments, and educational institutions to accelerate progress in the repair industry.

As part of the "visioning" process, each goal has been "road mapped" to establish strategies and action plans. A major part of the road-mapping task was to examine critically the suggested dates by which completion of strategies related to the goals could be reasonably expected and then to construct a timetable of goals. The timetable is needed because many goals are dependent on achieving other goals; thus, the timetable will help define the order in which goals must be achieved.

Industry leadership teams will use the Vision 2020 documents (goals and road maps) to guide industry activities by prioritizing efforts and resources to the established goals and action plans. Research and material organizations will use the established needs to prioritize research and development projects. Contractors and engineers will use this document to better understand the current state of the concrete repair industry and develop ideas for implementation of industry-envisioned improvements. Owners will understand that we take our industry very seriously and will use these tools to help them understand their structures and continued investments in repair and protection.

10.12.3 Unified Vision and Goals

The rehabilitation in the concrete industry is very diversified. More often than not, the work is not done properly, causing a bad image of the profession. This makes a proper and unified approach more meaningful to secure its future. This gave rise to Vision 2020, which was discussed by leaders in various aspects of the industry. Vision 2020 is a model for achieving the goal of a clear vision. This will happen only once, in the year 2020, as leaders representing a cross section of the industry, such as materials, equipment, industry cooperation, research and funding, professional practice, design methodology, environmental impact, workforce supply, and client's education, meet to achieve the perfect vision. One unified approach will result in overall improvements in repair quality, reduced repair cost, enhanced safety of workers, and, most importantly, the public by providing a cost-effective solution.

The detailed discussion led to 13 key goals and related strategies of Vision 2020. The areas they represent are given here to summarize the document:

1. Establish the mechanism(s) for industry cooperation to facilitate better and faster worldwide education of concrete rehabilitation technology and transfer the knowledge to all those who need it.
2. Ways to accelerate the process of such dissemination within the industry.
3. Create a standard and code, if possible, to carry the investigation, design, use of materials, and field and inspection practice. Such documents will help establish clear responsibilities and authorities of all participants and will provide local building officials who will regulate the process from the perspective of public safety.
4. Develop performance-based specifications, which will allow for generic and imaginative repair tools in designs to improve product.

5. Improve repair material design and performance to minimize and to improve structural capacity following the requirements of the construction.
6. Development of user-friendly repair materials and methods minimize the adverse effects on the environment and on workers and the public.
7. Developing methods to estimate repair system performance based upon models with experience.
8. Establish ways to eliminate duplication and to focus resources on important projects.
9. Bring together as many professionals from the rehabilitation practice to support the growing need of the industry.
10. Develop proper documentation to reduce conflicts, rework, and claims resulting from disagreements among the various parties involved to avoid lawsuits.
11. Implement proper client education/training by using recent technology to increase awareness of the effects of deterioration to reduce the risks to protect their investments.
12. Develop suitably improved methods for accurate and thorough condition assessment.
13. Devise suitable repair systems for efficiency in work and to reduce failure.

Additional information and the full report is found in *Vision 2020: A Vision for the Concrete Repair Protection and Strengthening Industry.*[20]

10.13 CONCLUDING REMARKS

FRPs have become increasingly popular due to their various advantages over other conventional methods of strengthening. In this chapter, the columns found unsafe against axial loads were strengthened using a fiber wrapping system. Both carbon fibers are used for the purpose of wrapping. The complete theoretical concepts are provided along with a sample calculation showing the details of the design of strengthening. Prestressing helps achieve a linear load deflection curve for higher levels of loading, thus extending the operating levels of the beam.

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APPENDIX: DESIGN EXAMPLE FOR STRENGTHENING OF CIRCULAR CONCRETE COLUMN

Consider a problem of column strengthening frequently encountered in real-life situations. The problem is to design the strengthening using concrete jacketing, steel jacketing, and FRP wrapping.

Given

Diameter of column, D = 400 mm
Area of reinforcement, A_{sc} = 8–16Φ (1608 mm^2)
Thus, area of concrete, $A_c = \pi*400^2/4 - 1608 = 124{,}055.77\ mm^2$
Grade of concrete = M15 (f_{ck} = 15 MPa)
Grade of steel = HYSD (f_y = 415 MPa)

Required

To increase the axial load capacity by 50%
Existing axial load capacity, $P_u = 0.4 f_{ck} A_c + 0.67 f_y A_{sc}$
Thus, P_u = 0.4*15*124055.77 + 0.67*415*1608 = 1191.44 kN = 1200 kN (say)
Required axial load capacity, $P_{u,reqd}$ = 1.5*1200 = 1800 kN

Design by Concrete Jacketing

For concrete jacketing, the minimum allowable jacket thickness = 100 mm and minimum grade of concrete in jacket = M20 (at least 5 MPa in excess of existing concrete grade). Let us provide a 100-mm-thick jacket of M20 grade concrete. Thus,

New diameter of column = 400 + 100 + 100 = 600 mm
Area of jacket, $A_j = \pi*(600^2 - 400^2)/4 = 157{,}079.5\ mm^2$

Assuming 1% reinforcement in jacket:

Area of longitudinal reinforcement in jacket, A_{scj} = 1570.80 mm^2

Let us provide 8–16Φ bars in jacket (1608 mm^2). Now,

Total area of reinforcement, A_{sc} = 1608 + 1608 = 3216 mm^2
New area of concrete in jacket, A_{cj} = 157,079.5 – 1608 = 155,471.5 mm^2

$$P_u = 0.4*15*124{,}055.77 + 0.4*20*155{,}471.5 + 0.67*415*3216$$
$$= 2882.32\ kN > 1800\ kN\ (OK)$$

It may be noted that although we have some margin to reduce the area, according to codal recommendations, this is the minimum possible design.

Percentage increase in weight of the column = $100*(600^2 - 400^2)/400^2 = 125.0\%$

Thus, the weight of the column has become *more than twofold* to increase the capacity by 1.5-fold.

Percentage increase in stiffness of column = $100*(600^4 - 400^4)/400^4 = 406.25\%$

Thus, the stiffness of the column has become *more than fivefold* to increase the capacity by 1.5-fold.

Design by Steel Jacketing

Diameter of existing column, $D = 400$ mm
Minimum allowable thickness of nonshrinkable grout = 25 mm

Therefore, jacket diameter, $d_j = 450$ mm. Now,

$$P_{u,reqd} = 1800 \text{ kN}$$

The existing axial load capacity is to be increased by increasing the compressive strength of concrete by providing confinement. The required cube strength $f_{ck,reqd}$ can be found as

$$P_{u,reqd} = 0.4 f_{ck,reqd} A_c + 0.67 f_y A_{sc}$$

$$1800*10^3 = 0.4*f^*_{ck,reqd}124{,}055.77 + 0.67*415*1608$$

Thus,

$$f_{ck,reqd} = 27.26 \text{ N/mm}^2$$

Therefore,

$$f_{cc} = 0.8 f_{ck,reqd} = 21.81 \text{ N/mm}^2$$

and

$$f_c = 0.8 f_{ck} = 12 \text{ N/mm}^2$$

Now, effective cylinder strength of confined concrete is

$$f_{cc} = f_c\left(2.254\sqrt{\left(1 + 7.94 f_l/f_c\right)} - 2 f_l/f_c - 1.254\right)$$

$$21.81 = 12*\left(2.254\sqrt{\left(1 + 7.94*f_l/12\right)} - 2f_l/12 - 1.254\right)$$

$$3.072 = 2.254\sqrt{\left(1 + 0.6617f_l\right)} - 0.1667f_l$$

Solving, we get effective lateral confining pressure as

$$f_l = 1.907 \text{ N/mm}^2$$

Considering allowable stress in steel jacket as 0.6*250 = 150 MPa and taking a factor of 0.67 for corrosion, we get

$$1.907 = 0.67*2*(0.6*250)*t_j/450$$

Thus, thickness of steel jacket t_j = 4.27 mm.

Let us provide a steel jacket of 5-mm thickness around the column with 25-mm grout between the column surface and jacket.

Percentage Increase in Column Weight

Additional weight per meter run = 78.7(π*0.45*0.005) + 24(π*0.425*0.05) = 2.16 kN/m
Original weight per meter = 25*(π*0.40^2)/4 = 3.14 kN/m
Percentage weight increase = 100*2.16/3.14 = 68.78%

Thus, the increase in weight is less than that for concrete jacketing but is still very significant. We require increasing the weight by two-thirds of original weight in order to increase the axial load capacity by 1.5-fold.

Percentage Increase in Column Stiffness

E for concrete = 5000*$(15)^{0.5}$ = 19,365 MPa
Initial EI = 25,000

Thus, the increase in weight is less than that for concrete jacketing but is still very significant. We require increasing the weight by two-thirds of original weight in order to increase the axial load capacity by 1.5-fold.

Design by FRP Wrapping

As calculated in "Percentage Increase in Column Stiffness," effective confining pressure required

$$f_l = 1.907 \text{ N/mm}^2$$

For R&M C-sheet 240, we have ultimate tensile strength, f_{fu} = 3800 MPa. Assuming only 50% strength development, we have

$$1.907 = 2*(0.5*3800)*t_j/400$$

which gives required jacket thickness, t_j = 0.201 mm.

Provide one layer of 430 gsm R&M C-sheet jacket (t_j = 0.234 mm) around the column.

Weight density of fiber = 17 kN/m^3
Additional weight per meter run due to fiber = 17(π*0.4*0.000176) = 0.00376 kN/m
Original weight per meter (as calculated in "Percentage Increase in Column Stiffness") = 3.14 kN/m
Percentage weight added to the column = 100*0.00376/3.14 = 0.12% (negligible)

These calculations indicate that there is a negligible mass increase in column due to fiber wrapping.

11 Global Sustainability and Concrete

Edward J. Martin

CONTENTS

11.1 PREVIEW

The term *sustainability* is amorphous in the sense that it has fallen into general use in maintenance of the environment and preserving environmental quality while actually having little chance of being achieved. The term generally carries the meaning of no negative impact on the environment. Achieving no negative impact could only apply in the case of renewable resources, since even minor utilization rates of nonrenewable resources would suggest that sustainability is not possible unless the resource in question was no longer required to support life, health, environmental quality, or the economy.

The environment could only be perfectly sustained (i.e., supported continuously for a very long time)* by zero utilization of nonrenewable resources and controlled use of renewable resources limited to the rate of reproduction. Neither of these outcomes is likely to occur. Indeed, while the term is in general use, the community has probably conceded that true sustainability is not possible. The current trend in analysis is to compare options and to choose for implementation, whenever possible, one or more that result in less utilization of resources and energy and lower impact on environmental quality. Often, the utilization and impacts cannot be quantitatively assessed, although some tools exist that can assist in arriving at decisions about design and construction choices even through, perhaps, assisted intuitiveness.

11.2 QUANTITATIVE SUSTAINABILITY OF CONCRETE

11.2.1 ATHENA Ecocalculator

An analysis was conducted to estimate concrete sustainability in a quantitative sense by comparing the environmental impact of using concrete and steel in an admittedly small fictional building of 1000 $ft.^2$. The analysis was done using ATHENA Ecocalculator,† the free version of the full-scale ATHENA Impact Estimator. The Impact Estimator has many more options than are available on the "Calculator" and includes the ability to estimate the "warming potential" in kilograms of equivalent CO_2.

The Calculator allows consideration of six construction elements (shown in Table 11.1). A wide range of choices are available within each element in an Excel spreadsheet format. The spreadsheet calculates the totals, as shown in Table 11.2. The largest impact in choosing concrete over steel options is the 47% savings in energy expended for the manufacture and use of the resources represented in the elements chosen. The air and water pollution indexes are significantly lower; the water pollution index for the steel options is over five times greater than for the concrete options. Finally, for the options chosen, there is even an overall insulation "R" value advantage for the concrete options.

* This definition is found in the Oxford American Dictionary, Oxford University Press, 1999. Interestingly, this dictionary (among others) does not define *sustainability* separately.

† ATHENA is a registered trademark of the Athena Sustainable Materials Institute, Merrickville, Ontario, Canada. The Ecocalculator can be downloaded at http://www.athenasmi.org/tools/ecoCalculator/index.html.

TABLE 11.1
Options Chosen for the ATHENA Ecocalculator Exercise

Construction Elements	Concrete Options	Steel Options
Columns/beams	Concrete/concrete	Wide flange steel/wide flange steel
Intermediate floors	Concrete hollow core slab	Open web, steel joist, steel decking, concrete topping
Exterior walls	CIP concrete, EIFS, latex paint; R = 15.99	2 × 4 steel stud, 16-in. o/c, brick cladding, gypsum board sheathing, vapor barrier, latex paint; R = 11.86
Windows	Curtain wall viewable glazing; R = 1.67	Curtain wall viewable glazing; R = 1.67
Interior walls	6-in. concrete block, latex paint each side	Steel stud, 16 in. o/c gypsum board, latex paint
Roof	Precast double T, modified bitumen, vapor barrier, rigid insulation, latex paint; R = 20.74	Open web steel joist with steel decking, 4-ply built-up roofing, vapor barrier, rigid insulation, gypsum board, latex paint; R = 21.88

TABLE 11.2
Results of Applying ATHENA Ecocalculator to a Fictional High-Rise Building

	Primary Energy Total (MMBtu)	GWP Total (tons)	Weighted Resource Use Total (tons)	Air Pollution Index Total	Water Pollution Index Total
1000-ft.^{2} high-rise; concrete options	2475	255	980	51,054	29.41
1000-ft.^{2} high-rise; steel options	3632	267	646	60,069	182.63
Concrete vs. steel	–47%	–5%	+34%	–18%	–520%

11.3 QUANTITATIVE SUSTAINABILITY OF CONCRETE COMPARING TWO BEAMS

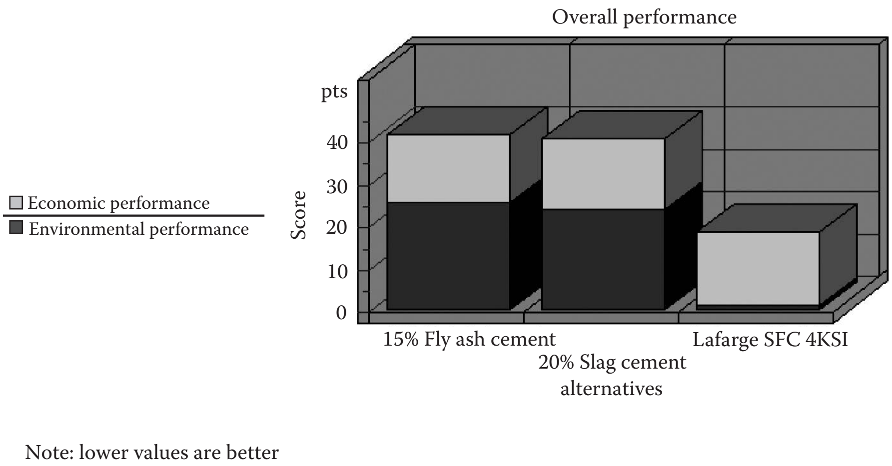
A similar analysis by Struble and Godfrey[1] examined the difference in impact for a pair of hypothetical beams: one of reinforced concrete and one of flanged steel. In this case, the resource use difference corresponds to the previous results: over twice as high for reinforced concrete. The energy use for the steel beam was 64% higher than for the reinforced concrete beam. The steel beam water pollution index was almost three times that for concrete, and the corresponding air pollution index was 22% higher; the latter was virtually the same as that of the more complex example that was given before. The so-called "warming potential" (kilograms of equivalent CO_2) was actually slightly lower for steel (about 13%), but since CO_2 is only partially responsible—allegedly at best—an analysis should include potentially more important greenhouse gases (GHGs) such as water vapor and methane.

It is useful to examine the relative impacts of construction materials carefully when design and construction options are being considered, given the following[2]: "The production of one ton of Portland cement generates approximately one ton of carbon dioxide and requires up to 7000 MJ of electrical power and fuel energy. It is evident that the concrete industry significantly impacts the ecology of our planet."

On the other hand, aluminum and steel and other construction materials possess significant impacts as well and can be shown to be higher than those of concrete in many cases.

11.3.1 The NIST BEES Calculator

The National Institute of Standards and Technology (NIST) Building for Environmental and Economic Sustainability (BEES) overall performance of three selections for *beams* equally weighted for economic and environmental performance is given in Figure 11.1 for 15% fly ash cement beam, 20% slag cement, and Lafarge silica fume cement (SFC; http://www.lafargenorthamerica.com/Lafarge_sustainable_development-Sustainable_report_2009.pdf)—all at 4KSI. The numerical values for the BEES alternative evaluation calculations are shown in the table in Figure 11.1. The Lafarge environmental advantage is quite striking even compared to the 15% fly ash option.

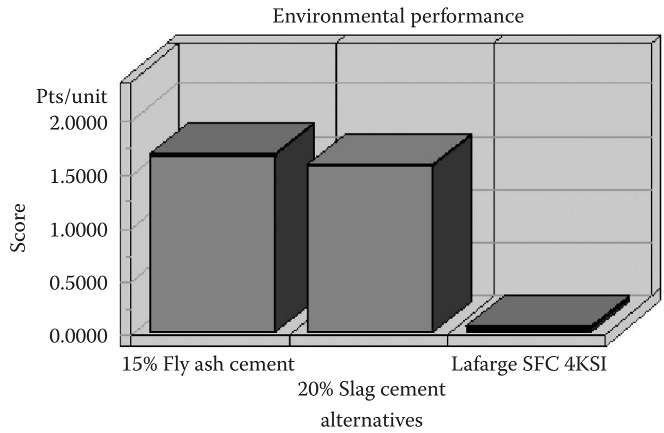


Category	15% Fly beam	20% Slag beam	Lafarge SFC
Economic perform—50%	16.2	16.5	17.4
Environmental perform—50%	25.2	23.8	1.0
Total	41.4	40.3	18.4

FIGURE 11.1 BEES evaluation calculations for a three-beam set.

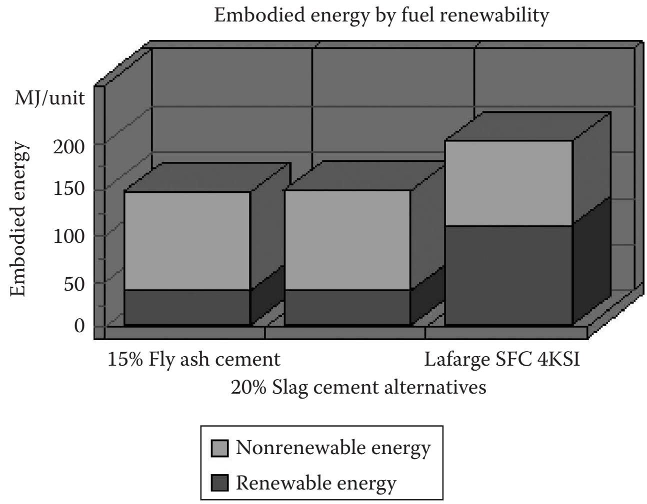
Lafarge SF™ cement is Portland SFC produced by intergrinding Portland cement clinker, silica fume, and gypsum. Lafarge SF cement can reportedly be used to produce concrete with a significantly higher compressive strength than that of normal concrete. The use of these materials in concrete production consumes less energy and offers improved efficiency and building performance. The environmental performance is apparent from the analysis. These materials can also be used to achieve Leadership in Energy and Environmental Design (LEED) points.[3]

For this example, the details of the environmental performance are provided in Figure 11.2. The weighting factors shown for the environmental categories are from



Category	15% Fly beam	20% Slag beam	Lafarge SFC
Acidification—5%	0.0000	0.0000	0.0000
Crit. air pollutants—6%	0.0011	0.0011	0.0013
Ecology toxicity—11%	0.0122	0.0188	0.0120
Eutrophication—5%	0.0009	0.0009	0.0009
Fossil fuel depl.—5%	0.0012	0.0012	0.0013
Global warning—16%	0.0080	0.0079	0.0132
Habitat alteration—16%	0.0000	0.0000	0.0000
Human health—11%	1.6579	1.5623	0.0345
Indoor air—11%	0.0000	0.0000	0.0000
Ozone depletion—5%	0.0000	0.0000	0.0000
Smog—6%	0.0026	0.0025	0.0027
Water intake—3%	0.0001	0.0001	0.0001
Total	1.6840	1.5878	1.0660

FIGURE 11.2 Details of the BEES environmental performance evaluation.



Category	15% Fly beam	20% Slag beam	Lafarge SFC
Nonrenewable energy	108.00	109.00	92.50
Renewable energy	38.30	38.30	109.00
Total	146.30	147.30	201.50

FIGURE 11.3 Embodied energy for the beam set.

the US Environmental Protection Agency (EPA) by its Science Advisory Board (SAB) for use during the development of BEES. Of course, a wide range of choices could be made for the weighting factors. The SAB highest-impact categories are clearly global warming and habitat alteration. The relative weights for the other categories are apparent from the values shown.

Energy considerations are important when considering construction materials and techniques. Fuel usage for production of cement may be either renewable or nonrenewable. See Figure 11.3 for comparisons. Whereas the total energy utilization for production of Lafarge cement is higher, the use of nonrenewable energy (coal, oil, etc.) is lower than the other two, and renewable energy utilization is higher (apparently, Lafarge makes significant use of solar energy especially in foreign plants), providing a degree of offset in terms of energy utilization against the higher overall requirement.

11.3.2 Using the Waste Reduction Model

The EPA's waste reduction model (WARM)* is another life cycle tool capable of evaluating the GHG and energy impacts of coal fly ash substitution in concrete.

* See the WARM model at http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_Form.html.

TABLE 11.3
Comparison of WARM and BEES Unit Impacts

	Impact per 1-MT Coal Fly Ash as Cement Replacement	
	WARM[b]	BEES[c]
Avoided energy (million Btu)	5.26	4.45
Avoided CO_2 (MT)	NA[a]	0.70
Avoided CH_4 (MT)	NA[a]	0
MT CO_2 equivalent ($MTCO_2E$)	0.96	0.71
MT carbon equivalent (MTCE)	0.26	0.20

[a] WARM does not report these values.
[b] WARM impacts on a short-ton, coal fly ash basis were converted to a metric ton basis by multiplying each impact by 1.102 short tons/MT.
[c] BEES impacts for avoided CO_2 and CH_4 were converted to $MTCO_2E$ and MTCE using the greenhouse gas equivalency calculator.

For comparison with BEES results for coal fly ash substitution, the avoided GHG and energy impacts per metric ton of coal fly ash substitution were calculated using WARM. Table 11.3 shows a comparison of the energy and GHG unit impacts derived from WARM and BEES.[4]

11.3.3 Recycled Content Tool

Emission factors that drive both the recycled content (ReCon) tool and WARM have been updated in WARM as of August 2008 but not yet updated in ReCon. The version of ReCon that is currently available therefore may produce outputs inconsistent with the latest version of WARM but does not include concrete as an option. ReCon is to be updated in 2011.*

11.3.4 Beneficial Reuse Models for Road Construction

BenReMod is a suite of beneficial reuse models developed by the US EPA specifically for comparing different materials that can be used in road construction. The models were developed by the University of Toledo (Ohio) and are currently available for use except for the human risk model portion of the suite, which is under development.[5] The life cycle assessment (BenReMod-LCA) module of the model was used to compare several types of road construction material combinations that could be used in road construction, largely comparing asphalt, asphalt concrete, and concrete combinations with recycled materials. Five simulations were run with the composition characteristics shown in Table 11.4.

* Personal communication, Jennifer Brady, US EPA, December 2009.

TABLE 11.4
BenReMod LCA Comparison Simulation[a]

Composition	Natural Aggregate	Asphalt	Cement	Fly Ash	Bottom Ash
Asphalt (HMA)	94	4	0	0	0
Fly ash + cement + aggregate	75	0	5	20	0
Bottom ash + cement + aggregate	75	0	5	0	20
Asphalt (HMA) + fly ash + aggregate	90	4	0	6	0
Asphalt (HMA) + bottom ash + aggregate	90	4	0	0	6

Note: HMA, hot mix asphalt.
[a] Volume percent.

For each composition case, the simulations were done for a road surface 4 in. thick, 10 m wide, and 1600 m long. Sources of recycled material were always assumed to be 20 km distant, whereas cement/asphalt and/or natural aggregate were always assumed to be 10 km away. A 14-ton truck was assumed for all transport, and a landfill was assumed to be in Ohio (used only for cost calculations). By keeping all the factors other than composition the same, a useful comparison may be made.

The system calculates associated electricity and oil consumption for production and transportation of the material, and cost, energy consumption, and contaminant emissions associated with use of a given material in road construction are determined. Contaminant emissions are then aggregated in various impact categories such as energy, global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), fresh aquatic ecotoxicity potential (FAETP), fresh sediment ecotoxicity potential (FSETP), and terrestrial ecotoxicity potential (TETP).

The resultant graphics for all the determinations are similar to those given for "cost" in Figure 11.4. The lowest cost simulation is item 3 in Table 11.4, the *bottom ash + cement + aggregate* option, and the second lowest is the second: *fly ash + cement + aggregate*. Thus, both concrete options exhibit the lowest cost for materials but not necessarily for transportation. The transport distances were kept at a minimum so as not to dominate the analysis. The asphalt and asphalt concrete options exhibit about the same costs and are at least one-third higher than concrete. Energy utilization for both concrete options is lower than asphalt and asphalt concrete (Table 11.5).

Table 11.5 lists the rankings for the other aspects calculated. Although the model is supposed to perform LCA analysis, lifetime of concrete versus asphalt options is not listed in the manual for operation of the models. The toxicity aspects listed in the last four columns of Table 11.5 may be expected to be higher for concrete than for asphalt and asphalt concrete options because of the potential leaching of heavy metals from the ash components, while these components are expected to be bound for the asphaltic options. Concrete may be expected to be more durable than asphaltic composites, so replacement of concrete road options may be expected to be less frequent. Thus, over the long term, the toxicity of asphaltic options may approach those of concrete options. This same consideration may apply to the link slab vs.

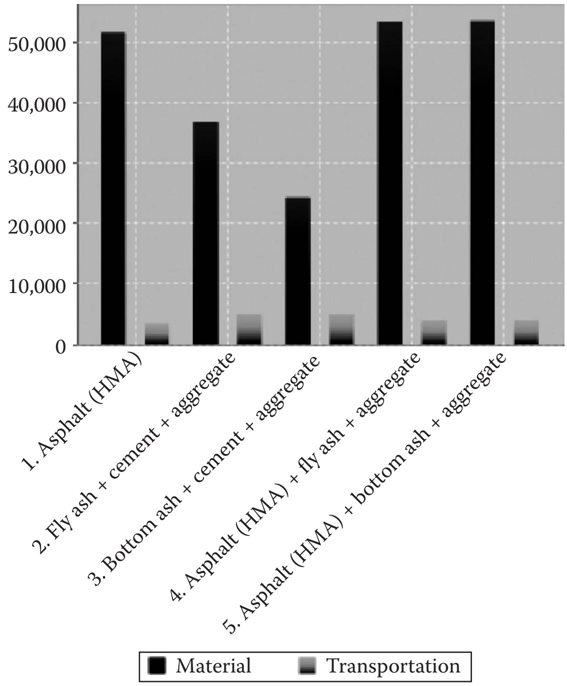


FIGURE 11.4 Cost comparisons for the simulations given in Table 11.5. (The order of the results shown on the abscissa is the same as that given in Table 11.4.)

TABLE 11.5
Rankings for Simulations

Composition	Cost	Energy	GWP[a]	AP[b]	HTP[c]	FAETP	FSETP	TETP
Asphalt (HMA)	3	3	2	1	–	1	1	1
Fly ash + cement + aggregate	2	2	1	1	1	3	3	3
Bottom ash + cement + aggregate	1	1	1	1	1	2	2	2
Asphalt (HMA) + fly ash + aggregate	3	–	2	1	–	–	–	–
Asphalt (HMA) + bottom ash + aggregate	3	–	2	1	–	–	–	–

[a] The GWP for concrete is very much higher because of the large energy requirement for producing cement.
[b] The AP for all options is the same; includes both SO_x and NO_x—thus the comparability.
[c] From leaching into the groundwater only.

conventional bridge options discussed in Section 11.4. Life cycle analysis (LCA) must *truly* compare alternatives over the long term.

11.3.5 Life Cycle Analysis and Factors Affecting Sustainability

LCA is particularly important in the case of systems that have long lives—characteristic of concrete systems—because of the factors that may change over long periods and the potential effect that these changes may have on the assessment of sustainability. In the case of most built-environment systems, concrete has a long lifetime. Bridges, for example, are expected to survive for decades, and, during these extended periods, many changes will likely occur. Vehicle mileage rates may improve, and vehicle miles traveled may increase or decrease, both of which will impact energy considerations and, of course, vehicle emissions.

A recent study examined LCA factors related to sustainability.[6] Engineered cementitious composite (ECC) materials used for link slab replacements were compared to conventional concrete designs (with steel expansion joints). ECC is a family of high-performance, fiber-reinforced composites that have the benefits of concrete, such as great compressive strength, but eliminate a key failure mode for concrete: its brittleness. ECC materials are capable of ductile behavior much like metal and can thus be used in place of a conventional expansion joint.

The ECC link slab design generally performs better from energy consumption, environmental pollution, and life cycle cost perspectives. It consumes about 40% less total primary energy and produces approximately 40% less carbon dioxide. The ECC link slab design also produces a total life cycle cost advantage of 14%, although this advantage decreases as the discount rate used in the model rises. The schematic representation is shown in Figure 11.5. Link slabs are a strategic application of ECC. By replacing the steel expansion joints found in most reinforced concrete bridge decks, the link slabs eliminate key failure modes for bridge deck deterioration. The replacement of expansion joints is possible because of ECC's ultra-high ductility, which can accommodate thermal expansion and contraction of the bridge along with bending deformation and thus eliminate the need for expansion joints. The ECC compositions used for the analyses are given in Table 11.6.[7]

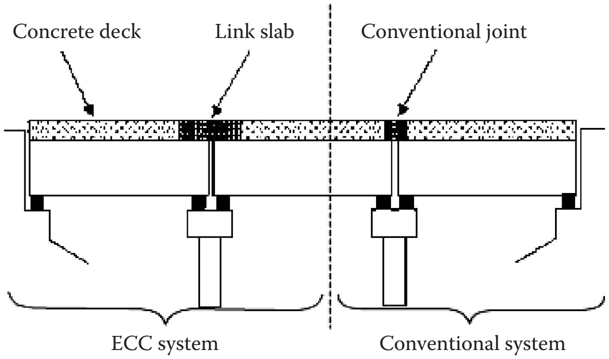


FIGURE 11.5 The link slab and conventional bridge slab design.

TABLE 11.6
Composition of ECC and Conventional Concrete Mix Designs

Component Material (g/L)	ECC Material	Conventional Concrete
Cement	578	474
Gravel	–	938
Sand	462	655
Fly ash	393	–
PVA fiber[a]	26	–
HRWR[b]	7.5	–
Water	298	200

Source: Kendall, A., Concrete infrastructure sustainability: Life cycle metrics, materials design, and optimized distribution of cement production. Center for Sustainable Systems, University of Michigan. Available at http://css.snre.umich.edu/css_doc/CSS07-07.pdf, 2007.

[a] Polyvinyl alcohol.

[b] Formaldehyde-based water reducer.

The study illustrates the advantages of using a life cycle approach over a short-term analysis. The conventional bridge design would be the choice, although the LCA of the link slab design possesses clear cost advantages. For example, the material energy intensity—the amount of energy consumed in the production of the material, beginning with raw material extraction through the processing and manufacturing, along with the feedstock energy, which is the energy embodied within the material itself—is about 110% higher for ECC defined in this study than for conventional concrete. This finding alone would lead to the conclusion that the conventional design is preferred over the ECC, using a short-term analysis.

However, the GWP (equivalent CO_2 for CO_2, methane, and nitrous oxide) is 40% less for ECC than for conventional concrete. The total primary energy (refers not only to energy directly consumed but also to the upstream energy requirements to produce and deliver the fuel or energy carrier directly consumed) is also about 40% higher for conventional concrete. The LCA for both systems includes traffic, construction, materials, distribution, and end of life. The components of the analysis include total primary energy; CO_2; CO; nonmethane hydrocarbons; methane; particulate matter, 10 μm; nitrogen oxides (NO_x); nitrous oxide; ammonia; biochemical oxygen demand; chemical oxygen demand; dissolved matter; nitrates; and phosphates.

11.3.6 Green Highways Program and Highway Sustainability Considerations

In 2005, the US EPA started the Green Highways Initiative as an instrument for coordinating environmentalism and transportation. Longevity is a key aspect of the use of concrete in pavements. It is common to find 50-year lifetimes for US concrete highways. I-10 east of Los Angeles was originally constructed in 1946 as part of US Route 66. It was ground in 1965 as a part of the first continuous grinding project in North America in order to correct joint spalling and faulting. It was reground in 1984, and in 1997, the 51-year-old was ground again. Today, the concrete is carrying 240,000 vehicles per day. Route 23 in Minnesota was constructed in 1948. The present serviceability rating (PSR) after about 50 years is 3.1 against a PSR of 4.1 rated as "very good." Some examples are even older, with one example in San Antonio built in the early 1900s and still serviceable today.[8]

The rigid structure of concrete in highway applications is claimed to have a positive impact on highway vehicle mileage and, consequently, fuel consumption. The National Research Council of Canada conducted a detailed study of heavy trucks and passenger cars on concrete, asphalt, and composite (concrete with an asphalt coating) highways. Some significant conclusions are as follows[9]:

> At 100 km/h, on smooth roads, fuel consumption reductions were realised on all concrete roads when compared to asphalt. The savings ranged from 0.4 L/100 km to 0.7 L/100 km (0.8% to 1.8%) when compared to asphalt roads. These savings were realised for both empty and fully loaded vehicle conditions for four of the five seasons. All these differences were found to be statistically significant at the 95% level. The savings during the fifth season, Summer Night, were 0.25 L/100 km (0.4%)[;] however, these data were found to be not statistically significant.
>
> When comparing concrete roads to composite roads at 100 km/h, the results showed that fuel consumption savings ranged from 0.2 L/100 km to 1.5 L/100 km (0.8% to 3.1%) in favour of concrete. However, under Summer Day conditions, less fuel was consumed on the composite roads, as compared to concrete. The value of these savings was roughly 0.5 L/100 km (1.5%). All composite to concrete comparisons were found to be statistically significant except the Spring data, which was not statistically significant.

Both full and empty trailers showed fuel savings advantages for concrete pavements. All results were statistically significant.

There are a number of advantages accruing to the use of concrete on highway construction, including the following[10]:

- Concrete highways exhibit high sustainability because they last for long periods—many sections and full-length highways for several decades and a number for 50 years.
- A long-lasting highway requires less maintenance and fewer rehabilitation events. Less interruption in consistent traffic flow results in significant fuel savings.
- Pervious shoulders constructed with recycled concrete or pervious concrete shoulders reduce runoff. Also, pervious concrete paving for parking lots provides for some degree of groundwater recharge.

Table 11.7[11] illustrates that while ECC has superior mechanical properties, production of ECC imposes significantly higher environmental burdens due to the increased cement content of ECC, replaced by aggregate in concrete. It would seem on the basis of the table data that the ECC system causes too much environmental

TABLE 11.7
Properties and Material Sustainability Indicators for Concrete and Engineered Cementitious Composite

	Compressive Strength (MPa)	Tensile Stain Capacity (%)	Total Energy Use (MJ/L)	Solid Waste (kg/L)	CO_2 (g/L)
Concrete	35	0.02	2.68	0.152	407
ECC	65	5.0	8.08	0.373	975

Source: Li, V. C. et al., In *Proceedings, International Workshop on Sustainable Development and Concrete Technology*, Beijing, China, ed. E. K. Wang, 2004.

stress to result in consideration. However, the ECC system uses fewer days of construction. User delay, vehicle operating, and traffic crash costs were all lower with the ECC system. Also, while the lifetime of the conventional bridge system might be expected to be about 30 years, the expected lifetime of the ECC system could be twice as long.

The detailed life cycle cost analysis included the following segments: materials, construction, use, and end of life. The LCC analysis included eight modules of assessment:

1. Material cost, including distribution
2. Construction costs
3. End-of-life costs
4. Emission costs from the preceding three modules of assessment
5. Vehicle congestion emission costs
6. User delay costs
7. Traffic crash costs
8. Vehicle operating costs

For each of the life cycle cost stages, the ECC system had lower costs than those of the conventional system. Upfront costs, often used to compare alternatives, are a poor indicator of long-term costs. While the unit material costs for the ECC system are substantially higher, it exhibits lower material production and distribution costs over the 60-year lifetime examined.[12]

11.4 INSPECTION, MAINTENANCE, AND PRESERVATION ASPECTS OF SUSTAINABILITY

11.4.1 Comments on the Program in Germany

Inspections of roads and bridges are a critical part of the sustainability program in Germany.[13] The German standard DIN 1076 (3) requires inspection at certain intervals in order to manage infrastructure in an efficient and sustainable way: main inspections, simple inspections, inspections on special occasions, inspections according to special regulations, and regular observations. Main inspections are carried out regularly every 6 years; simple inspections are to be carried out 3 years after a main inspection. Besides the regular checks, special checks are required after special events or after a claim. The main inspections are executed as visual inspections with a hand near examination of the complete structure. Some field tests for deeper examination are frequently undertaken using special nondestructive testing equipment (e.g., Schmidt hammer to detect concrete strength, simple hammer to detect delaminations, and a test to determine concrete cover, primarily radar and sonar devices; see Figure 11.6).

The management system is life cycle-oriented. Most of the bridge and road network is relatively new, having been constructed between 1960 and 1980. Thus, while the expectation is for 70-year lifetimes, much of the transportation network requires extensive maintenance and rehabilitation. This aging aspect makes the German system considerably different from other systems in the developed world, which represent older systems for which replacement may be a dominant component of the sustainability effort. In addition to common corrosion damages, older prestressed concrete bridges show some severe weak points:

- Fatigue effects of tendons in coupling joints
- Low shear force capacity due to marginal shear reinforcement
- Rupture of tendons due to stress corrosion associated with imperfectly grouted ducts

The result is a program largely directed at repairing and preventing faults.

Similarly, the technology requirements are for those that are applicable for rehabilitation as opposed to new construction. Methods will include a multiplicity of

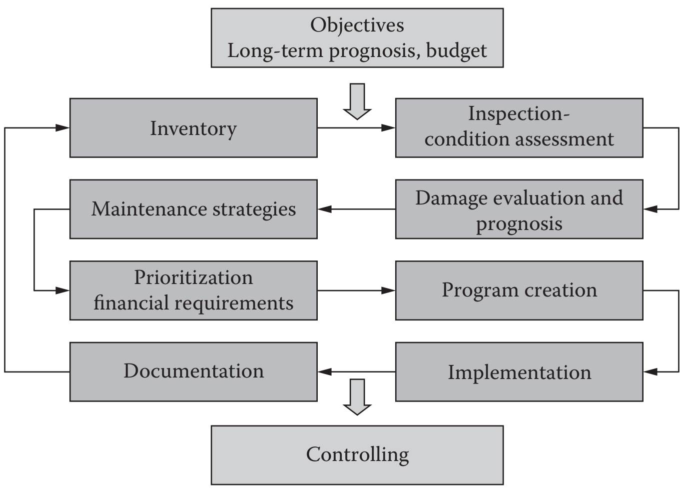


FIGURE 11.6 A scheme for road maintenance in Germany.

different methods (e.g., prestressed or slack carbon fiber-reinforced polymer sheets, external prestressing, additional reinforcement, injection of cracks and voids, and extension of concrete cross section by shotcrete).

11.4.2 Swiss KUBA[14]: A Comprehensive Road Structure Management System—Swiss Federal Roads Authority

The Swiss program is characterized by concern for the conditions of tunnels; this results in a somewhat unique consideration. Also, there is special concern for highways that are exposed to winter conditions for a significant portion of the year.

Figure 11.7 shows that the overall condition of the structures is good. It includes only bridges that were in existence before December 2006. The feeling is that the condition of the road structures in the system will remain stable as it has during the recent past. Thus, the amount of resources being spent on maintenance is likely to be found as adequate. There is currently public pressure to reduce spending on transportation infrastructure, so conditions may change as time passes.

11.4.3 Bridge Management System for the Western Cape Provincial Government, South Africa

As can be seen from Figure 11.8, the system is quite extensive. There are 2300 structures (850 bridges and 1450 major culverts) in the province's five district municipality regions and the Cape Town Unicity. (This does not include those under the jurisdiction of the city of Cape Town.) The rehabilitation strategy is to address the structures in the worst condition and within the highest use portions of the system.

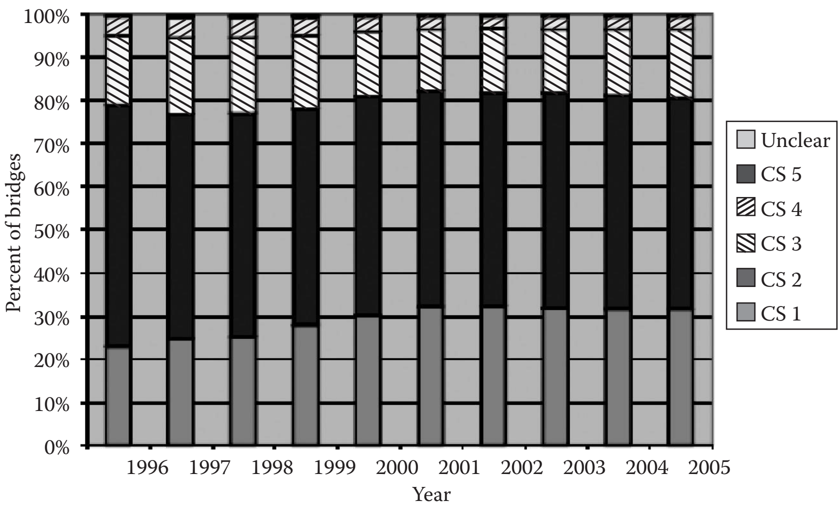


FIGURE 11.7 Condition states (CS) of bridges on national road network (CS 1 = best; CS 5 = worst).

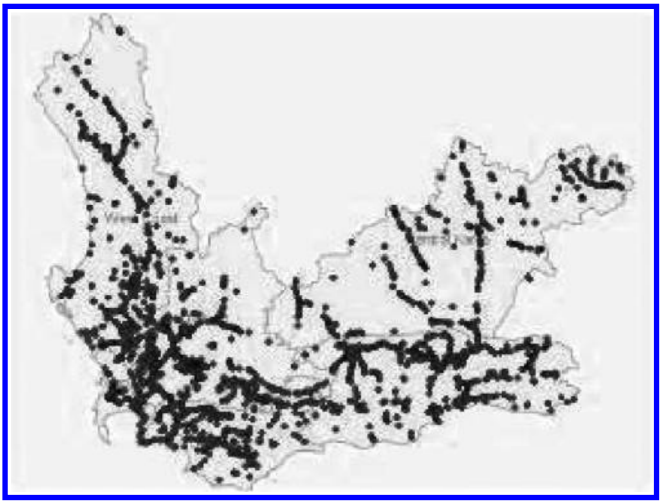


FIGURE 11.8 Map showing all structures in the bridge management system database.

A priority index value (PIV) approach has been developed, and those with a PIV of below 60 are requiring attention. About 175 bridges are in this category.

An attempt was made to "group" bridges requiring construction rehabilitation so that contracts could be awarded, constituting a "project." In order to accomplish the grouping, it was necessary to include within groups those bridges that scored a low priority but possessed a high benefit–cost rehabilitation score. The grouping results in environmental benefits from the point of view of fuel and resource utilization while the program is being implemented. Figure 11.9 illustrates the impact of focusing geographically on 65 bridges and major culverts in the Calitzdorp, Oudtshoorn, and De Rust areas.

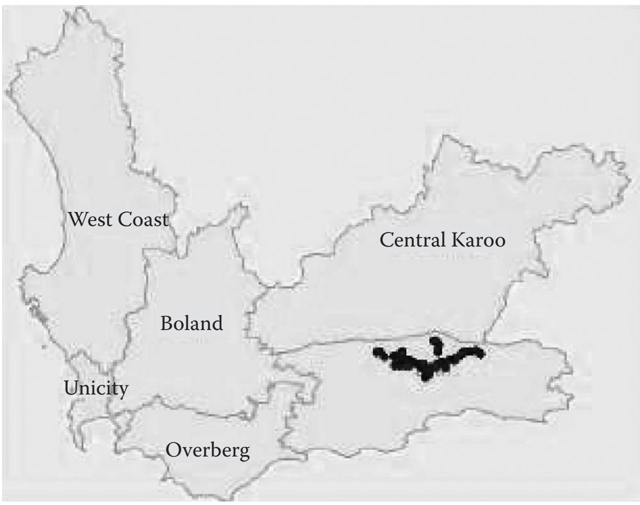


FIGURE 11.9 Map showing structures included in the rehabilitation project.

After completion of the repair work, all 65 of the structures were reinspected using the BMS assessment approach and reprioritized as part of the main database. As far as the priority rankings are concerned, more than 80% of these structures are now in the lower 60% of the priority list. The structures that were originally in the priority index < 60 category required structural repairs; all of these structures are now in the lower 60% of the priority list. As far as the condition rankings are concerned, all of the 65 repaired structures are in the lower 50% of the priority list.[15]

11.4.4 Considerations for Sustainability in New Zealand

There has been a recent surge of interest in sustainability in New Zealand:

> The government's commitment to sustainable development is stronger than ever, with the Prime Minister's recent opening address to Parliament firmly positioning it at the heart of the Government's policy platform. Comparing the quest for sustainability with New Zealand's nuclear free stance, the Prime Minister outlined a range of Government priorities designed to make New Zealand the "first nation to be truly sustainable." While critical of the Government's sustainable development policy, opposition leader John Key has also embraced it as a strategic issue by emphasizing the importance of balancing sustainable resource management with economic development."[16]

The paper from which the preceding quote was taken describes progress in the areas of durability, fire performance, thermal mass, acoustic performance, recycling, storm-water management, road construction, and demolition. There are limitations to implementation of the program. For example, supplementary cementitious materials (SCMs) are not widely available in New Zealand. However, fly ash is available, complying with the provisions of Type C according to the classification method contained in ASTM C 618-03. It has found general use at reasonable replacement levels in New Zealand. General-purpose cement is the most common cement type in New Zealand; blending of up to 5% mineral fillers and up to 1% processing additives is allowed. This has the benefit of reducing the embodied energy of finished cement.

In the period 1990–2000, the New Zealand cement industry reduced carbon dioxide emissions from thermal energy by some 18% and is still continuing to do so. Local research has shown that the combination of rigidity and the smooth surface of concrete paving reduces vehicle fuel consumption for heavy vehicles. Opus International Consultants and the Department of Mechanical Engineering at Canterbury University have established that the coarser the road surface is, the more the fuel used by cars. These results are similar to findings elsewhere.

It happens that New Zealand's reinforcing steel is made from 100% recycled, locally sourced scrap. The New Zealand steel reinforcement industry recycles some half a million tonnes of scrap steel per year, which is then used in reinforced concrete. Earthquake design requirements in the country have forced special considerations for the use of precast structures and appurtenances. Shortage of aggregate as a resource has undoubtedly enhanced the use of recycled concrete and crushing operations.

11.4.5 Concrete Sustainability Progress in China

Although fly ash concrete is increasingly utilized, the rate of consumption of fly ash by the cement and concrete industry is estimated to be very low, and some serious problems still exist in China. For example, in the north of China, a number of electric power plants are often located not far from coal mines but far from large urban areas and big projects. At the same time, many cement factories are also centralized in that region around mines, so in large urban areas, there is a lack of fly ash resources. Transport of fly ash, of course, increases its cost, and there is a concurrent lack of interest in using fly ash concrete. There is "a misconception among some engineers that the use of fly ash in concrete increases the…[likelihood] of reinforcement corrosion because the pozzolanic reaction…[may reduce] the pH."[17] There is another similar misconception in China that the use of fly ash in concrete makes the pavement poor in abrasion resistance. Both misconceptions result from accelerated evaluation testing methods used in the laboratory. This has blocked fly ash application in concrete.

There are some institutional barriers as well, but change is occurring. For example, the maximum fly ash content of 25%–50% by mass (significantly fewer limits elsewhere) of cementitious material (for reinforced concrete, the limit is only 15%–25%) is prescribed in a specification published by the National Transportation Department in 2000. There is movement to change the existing fly ash limitations by replacement with performance-based limits on fly ash content.[18]

About 700 million tons of cement were manufactured and consumed in China in 2002. Along with the vigorous development of electric power plants and ironworks, more than 150 million tons of coal ash and about 80 million tons of blast furnace slag were produced per year. Most of the latter was used in manufacturing normal and blended cement in China beginning in the late 1950s. Until recently, because cement with high early strength is favored on the market, a water/cement ratio of 0.44 was replaced by 0.50 for grading cement by the new national standard corresponding to the ISO standard. Ground slag powder is increasingly used as supplementary material in concrete, as it is elsewhere.

Weizu[18] states that the paradigm shift in scientific research and education has to be changed from a reductionist to a holistic model. China has a civilization spanning several millennia, and Confucian thinking emphasizes the unification of nature and humans. He hopes that the mentioned shift will be realized as soon as possible.

China currently produces one-half of the world's cement output. The Three Gorges Dam project is using belite (dicalcium silicate with other contaminant oxides)-based Portland cement, which can be produced while emitting 10% less carbon dioxide and exhibits an improvement in durability.[19] Dicalcium silicate is formed at a lower operating temperature (~1200°C–1300°C) than conventional Portland cement manufacturing temperatures (~1400°C). Results showed a lower clinkering temperature of about 100°C with corresponding lower CO_2 emissions. The 7-day cure strength was higher than for similar Portland cement concrete configurations. Durability testing showed "good properties" of freeze–thaw resistance, carbonation, and permeability resistance compared to Portland cement concrete.

11.4.6 Testing in the Persian Gulf Region

The hot and aggressive climate of the Persian Gulf poses special problems for durability of concrete structures and has a definite impact on maintenance as well as lifetime considerations. A study investigated the performance of concrete specimens containing various pozzolanic materials, blast furnace slag, trass, and silica fume.[20] Tests included compressive strength, permeability, chloride diffusion, corrosion of reinforcing bars (a special regional problem), and carbonation depth at various ages. All concrete mixtures containing pozzolans showed better performance when compared to control concrete mixtures.

The overall best performance was obtained with mixtures with trass cement, type II Portland cement, and silica fume. Severe reinforcement corrosion was observed with type V Portland cement after 4 years.

11.4.7 Japanese and European Standards for Self-Compacting Concrete[21,22]

Guidelines for self-compacting concrete (SCC) published by the Japanese Society of Civil Engineers[23] and European guidelines published by the European Federation of National Associations Representing for Concrete (EFNARC)[24] are available. A typical application example of SCC in Japan includes the two anchorages of the Akashi–Kaikyo (Straits) Bridge opened in April 1998, a suspension bridge with the longest span in the world (1991 m).[25]

SCC has been used commonly in precast and preformed concrete but much less in on-site applications, probably because SCC requires more sophisticated preparation and handling than conventional vibrated concrete. Additional complications occur because the mix must be properly designed and tested to assure compliance with the project specifications, and the ingredients and equipment used in developing the mix and testing should be the same ingredients and equipment used in the final mix for the project. Common concrete mixers can be used for SCC preparation and transport, but SCC is more sensitive to proper water content. Pozzolanic admixtures may be added at the plant or at the site, but preparation at the plant increases the cost to the supplier.

11.4.8 SCC Experience in India

Most Indian applications use the ENFARC guidelines for SCC (see Section 11.3).[26] Addition of fly ash in SCC increases fluidity of concrete, whereas rice husk ash (RHA) increases viscosity to concrete, improving segregation resistance of the concrete mix. The experimental study showed that fly ash and RHA blend well and improve overall workability, which is the objective of SCC. The increase in RHA content in SCC increases water demand and reduces the compressive strength of concrete samples tested. The increase in RHA content from 7.5 to 30 kg/m^3 raised the water requirement of the mix, thereby decreasing the 28-day strength of concrete from 38 to 27 MPa.

RHA is a common agricultural waste in India, whereas fly ash is an industrial waste from thermal power stations. Utilization of these waste products in concrete will help achieve an economical SCC mix, and it is felt that it may improve the microstructure and, consequently, the durability of concrete. Use of RHA and fly ash in concrete provides a solution to disposal problems and environmental pollution resulting from these wastes.

11.4.9 SCC Case in Cambodia[27]

It was determined that it was possible to produce SCC using raw materials found in Cambodia. Limestone powder is available in Cambodia, in Kompot and Battembang provinces, and was used in the study. Blast furnace slag and silica fume are available but, apparently, are high-cost items. RHA and rice-straw ash are commonly available, but it was felt that more research was needed to use these successfully. Many types of sand are available, and river sand was used. Coarse aggregate gravel and crushed stone are available from basalt, granite, limestone, or rhyolite. Crushed rhyolite was used because it is found near Phnom Penh.

"Ordinary Portland cement" available in Cambodia (type not given) was used. Superplasticizers are not available in Cambodia, but Viscocrete HE-10 was ordered from Vietnam. Thus, it was somewhat of a struggle to assemble the ingredients and pursue an acceptable SCC strategy, where sources are limited, and successfully test SCC in application.

11.5 SOME GLOBAL CONSIDERATIONS OF CONCRETE SUSTAINABILITY

The burgeoning development and construction programs in India and China and other high-growth countries, as well as repair and replacement in more developed countries, will result in a very high demand for cement and concrete. Among the primary concrete-making materials, the emission of carbon dioxide is significantly attributable to cement production:

> Modern cements contain an average of about 84% Portland cement clinker, and the clinker manufacturing process releases 0.9 tonne of CO_2 per tonne of clinker. Worldwide, the concrete industry consumed nearly 2.77 billion tonnes (3.05 billion tons) of cement in 2007, so the carbon footprint of the industry is obviously quite large.[28]

Kumar suggests three "tools" for global sustainability: (1) consume less concrete (e.g., radically increase service life of structures); (2) consume less cement in concrete mixtures (e.g., specify longer-term compressive strengths); and (3) consume less clinker in cement (e.g., concrete containing even as high as 50%–60% fly ash by mass of the total cementitious material shows high strength, low thermal and drying shrinkage, high resistance to cracking, high durability, and, consequently, excellent potential for use as a sustainable structural material for general construction).

Combined use of tools 1 and 2 is claimed to reduce cement utilization by 30%. If the average clinker factor for cement (mass ratio of clinker to cement) is reduced from 0.83

to 0.60, for example, the clinker requirement falls from 2.30 billion tonnes (2.50 billion tons) in 2010 to 1.18 billion tonnes (1.30 billion tons) per year in the year 2030.

11.6 NEW INTERNATIONAL CONSIDERATIONS

The information available at this time on the international platform relative to sustainability is minimal. Previous research over the past 10–15 years on plasticizers and waste-derived additives has now become applicable to the sustainability concept and movement in concrete structures and infrastructure development. The Tenth ACI International Conference on Advances in Concrete Technology and Sustainability Issues was held in October 2009 in Seville, Spain, and the schedule is available online.[29] The proceedings were reviewed for this chapter. In addition to the technical matters presented that relate directly to sustainability, presenters were from Italy, Iran, the Czech Republic, Belgium, Japan, Canada, Spain, Norway, Australia, Croatia, Denmark, South Korea, Northern Ireland, China, Switzerland, France, Saudi Arabia, Luxembourg, United Arab Emirates, and Turkey. This indicates the extent to which the attention to sustainability is spreading. Various topics of the proceedings are summarized above.

11.7 OTHER ENVIRONMENTAL CONSIDERATIONS FOR CONCRETE SUSTAINABILITY

11.7.1 Supplementary Cementitious Materials

SCMs are extensively used in concrete production and, subsequently, in virtually every type of concrete construction project.

11.7.2 GHG Production from Manufacture of Cement/Concrete

Among the industrial sources of GHGs, cement production ranks relatively high in the ranking, as shown in Figure 11.10. Steel GHG production is considerably higher; however, some portion of the lime production category must be included for assessing *concrete* production impact. It is important to understand that the warming potential of water vapor, easily as important as CO_2 as a GHG, is still not included in the estimates of GWP by the Intergovernmental Panel on Climate Change (IPCC)—consequently, the estimates in the Ecocalculator in the footnote at the beginning of this chapter claim that water vapor is short-lived and spatially inhomogeneous (whereas other GHGs are allegedly not). The inset in the figure is a reminder that the whole industrial production category accounts for less than 5% of the total GHG emissions; fossil fuel power production accounts for the highest fraction.

Figure 11.10[30] does not illustrate trends; the worldwide data gathered through the United Nations in Table 11.8 do to a certain extent. While CO_2 production in the industrial sector presents a definite downward trend and that from iron and steel production does as well, CO_2 from cement production decreases only in 2007. Again,

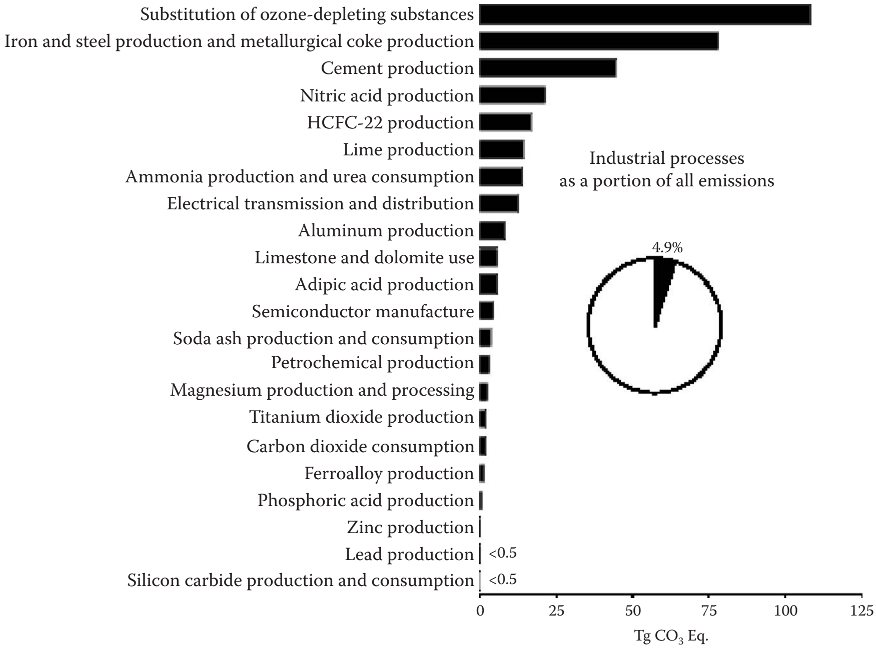


FIGURE 11.10 GHG production in the United States of various industrial sources in terragrams of equivalent CO_2 between 1990 and 2007. (Courtesy of Portland Cement Association. Available at http://www.cement.org/Briefingkit/image_captions.asp; US EPA. 2009. Inventory of US greenhouse gas emissions: Sources and sinks: 1990–2007. Available at http://www.epa.gov/climatechange/emissions/downloads09/InventoryUSGhG1990-2007.pdf.)

TABLE 11.8
Worldwide Emissions from Industrial Processes[a]

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	197.6	198.6	193.3	171.1	175.9	174.9
Iron and steel production	109.8	103.1	95.1	73.2	76.1	77.4
Cement production	33.3	36.8	41.2	45.9	46.6	44.5
Lime production	11.5	13.3	14.1	14.4	15.1	14.6
Limestone and dolomite use	5.1	6.7	5.1	6.8	8.0	6.2
Aluminum production	6.8	5.7	6.1	4.1	3.8	4.3

Source: Adapted from Inventory of US greenhouse gas emissions: Sources and sinks: 1990–2007, US EPA, April 2009.

[a] Terragrams of equivalent CO_2.

some portion of the lime production and limestone use emissions must be taken into account for consideration of concrete production.

The data reflect iron and steel *use* and cement *use* as well as changes to production emissions resulting from process changes. Decreases in production quantities will result in decreases in GHG production.

11.7.3 Proposed Legislation for Greenhouse Gas Emission Control

There is agreement that the legislation that affects the cement industry as a result of the several proposed bills will include carbon credits, and most will be "cap-and-trade" types. Optimally, there are a number of options for management of GHG emissions. These include[31]

- Use of more blended cements: slag, fly ash, fume, etc.
- Use of carbon-neutral fuels, renewables
- Adopting energy efficiency measures
- Carbon dioxide capture and storage
- Hybrid cement energy facilities—utilization of waste heat
- Use of noncement binders with lower specific CO_2 emissions (e.g., geopolymers)

Of these, the last three are costly and are not likely to become available in the short-term future. Therefore, a strategy that seems doable includes the following[32]:

- Conversion to clean alternative fuels
- Improvements in energy efficiency and technology in cement production
- Use of blended cements

Indeed, the use of blended cements/concrete looks very promising, as shown in Table 11.9,[33] largely because of the impetus for use of recycled material given by Section 6017(a) of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, P.L. 109-59, Aug. 10, 2005 (SAFETEA-LU), which directs the US EPA to "conduct a study to determine the extent to which procurement requirements, when fully implemented…may realize energy savings and environmental benefits attainable with substitution of recovered mineral components in cement used in cement or concrete projects." There are, of course, barriers to the use of recycled materials; however, the following are in significant excess supply, so availability is not one of the barriers: coal fly ash, foundry sand, flue gas desulfurization (FGD) gypsum, FGD dry scrubber material, power plant bottom ash, and cement kiln dust.

Federal guidelines allow that such recovered mineral components (RMCs) do not have to be procured if they (1) are not available within a reasonable period of time, (2) fail to meet the performance standards set forth in the applicable specifications or fail to meet the reasonable performance standards of the procuring agencies, or (3) are only available at an unreasonable price.

TABLE 11.9
Estimated Environmental Benefits of Using Coal Fly Ash, GGBFS, and Silica Fume as a Substitute for or Supplement to Portland Cement in Federal Concrete Projects

Metric Units	Historical Environmental Benefits: 2004–2005	Projected Environmental Benefits: Baseline Scenario 2005–2015[a]
Energy savings (billion MJ)	31.5	212.1
Water savings (billion L)	2.1	14.1
Avoided CO_2 equivalent (million MT)	3.8[b]	25.7[b]
Passenger cars not driven for 1 year[c] (million)	0.8[b]	5.7[b]
Passenger cars and light trucks not driven for 1 year[c] (million)	0.7[b]	4.7[b]
Avoided criteria pollutants (air) (thousand MT)	31.3	209.7
Avoided mercury (air) (MT)	0.3	1.9
Avoided soil emissions (MT)	0 (negligible)	0 (negligible)
Avoided end-of-life waste (MT)	0	0

Note: GGBFS, ground granulated blast furnace slag.

[a] Calculated as the sum of impacts for coal fly ash current use baseline and GGBFS and silica fume current use scenarios.

[b] Results reflect only coal fly ash impacts.

[c] These metrics are equivalent expressions of the avoided greenhouse gas metrics and do not represent additional benefits.

There are significant benefits to heavy use of RMCs in addition to the impact on GHG emissions, as shown in Table 11.9. Incidentally, the beneficial use modeling for the purposes of the EPA RMSC study utilized the BEES model referred to earlier in this chapter.

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12 Sustainable Concrete with Industrial and Postconsumer By-Product Materials

Tarun R. Naik and Rakesh Kumar

CONTENTS

12.1 INTRODUCTION

Sustainable concrete is the need of today. The ideology of developing sustainable infrastructures, resource conservation, and reduction in carbon footprint of concrete-based infrastructures are the main driving forces for a sustainable concrete. A sustainable concrete should have the following features: it should have a very low inherent energy requirement, be produced with little to no waste and with recycled materials, be highly durable, and ensure little adverse impact on the environment. Manufacturing sustainable concrete requires judicious use of natural resources and lower environmental impact in comparison with conventional concrete. This is generally achieved through reduced mining of natural resources required for the manufacture of concrete. This can be achieved by recycling of suitable industrial by-products such as coal-combustion by-products and other types of biomass ash, pulp, and paper mill residual solids, silica fume, ground granulated blast furnace slag, rice husk ash, limestone mining and processing by-products, cement kiln dust, waste-washed water, and other similar materials, and postconsumer materials such as used tires, plastics, glass, recycled concrete pavements, construction and demolition (C&D) debris, and other similar materials. These industrial and postconsumer materials are mostly used for the purpose of partial replacement of either the aggregates or cement in the production of concrete. Use of these materials not only reduces manufacturing cost and the adverse environmental effects of concrete but also improves the service life of the structures.

12.2 WHY SUSTAINABLE CONCRETE?

Portland cement-based concrete is used more widely than any other construction material because of its many benefits. Ordinary cement concrete typically contains about 12%–15% Portland cement, 8%–10% mixing water, and 75%–80% aggregates by mass. The current concrete construction practice is considered unsustainable as it consumes a huge quantity of natural resources such as stone, sand, and water every year. Each of the basic ingredients of concrete has some adverse environmental impact, and, therefore, they give rise to different sustainability issues. From an environmental point of view, Portland cement, the key ingredient of concrete, is not considered as an eco-friendly material as its production is energy intensive, uses large amounts of natural resources, and releases a significant amount of greenhouse gases (GHGs). About 1.7 tonnes of raw materials, such as limestone, clay, chalk, etc., are needed to manufacture 1 tonne of cement.[1] Each stage of cement production has some environmental effects. The energy consumption by the cement industry is more than 2% of the global primary energy consumption. However, the cement industry contributes over 7% of total anthropogenic CO_2 emissions.[2–5] Portland cement-based concrete is also a major consumer of natural resources—rock, minerals, potable water, and fossil fuel, which are increasing year by year, resulting in faster rate of depletion of such natural resources needed for the manufacture of both Portland cement and concrete. The production of Portland cement contributes to global climate change due to the release of GHGs,[5] principally CO_2 in the earth's atmosphere. Manufacturing of concrete and its products has a significant impact on the environment as the production of concrete releases GHGs, which include emissions from the mining of raw materials, transportation, construction, maintenance, demolition, and disposal or recycling processes at the end of life of the infrastructures constructed with concrete. In the light of limited natural resources and adverse impacts on global climate change, the concrete industry must play a vital role by encouraging the technology for the development of sustainable concrete for prolonged service life, conservation of natural resources, reduction in energy required, and minimization of GHG emissions from its manufacturing and transportation of concrete-making materials and products. The success of such technology mainly depends on local conditions, norms, and practices. Understanding of the environmental issues in the manufacturing activities of concrete and its products is the main driving force for the advent of sustainable concrete.

12.3 CONCEPT OF SUSTAINABLE CONCRETE

The concept of sustainable concrete includes recycling of suitable industrial by-products and/or postconsumer materials for the reduction and consumption of virgin natural resources and energy without compromising quality and service life by ensuring an improved quality construction. Sustainable concrete is an intelligent solution that mitigates the adverse effects of its manufacturing by consuming less energy and less natural resources (for example, recycling of suitable by-products from industry and postconsumer products, agricultural wastes, municipal waste, and other similar materials) in its manufacturing. Although the technical as well as economic benefits of the inclusion of certain industrial by-products in concrete have been documented for the past several decades, the total advantages derived from such uses allow these industrial by-product materials to be considered as a means to reduce the cost of the concrete and also be considered as essential ingredients for the manufacturing of a sustainable concrete. Similarly, suitable postconsumer materials such as used tires, plastics, glass, recycled concrete pavements, C&D debris, etc., can be used for the purpose of reduction of the carbon footprint and conservation of the natural resources required for sustainable concrete manufacturing. Judicious use of suitable industrial and postconsumer materials also increases the durability of concrete. There is a difference between durability for a few years, a few decades, a few centuries, and durability at reasonable cost contributing to sustainable development.

In this chapter, an overview of the recycling of some of the suitable industrial by-product materials, such as coal-combustion products (CCPs), foundry sand and slag, pulp and paper mill residuals, and ready-made concrete mixture wash water, as well as postconsumer materials, such as used tires, plastics, glass, and recycling of discarded concrete pavement slabs in the manufacturing of a sustainable concrete, has been presented.

12.4 INDUSTRIAL BY-PRODUCT MATERIALS IN SUSTAINABLE CONCRETE SYSTEM

12.4.1 Coal-Combustion By-Products

A CCP is a synonym for the combustion residue at coal-fired plants for generating steam for energy or for electric power. CCPs include fly ash (Figures 12.1 and 12.2), bottom ash (Figure 12.3), boiler slag (Figure 12.4), and fluidized bed combustion

FIGURE 12.1 A typical fly ash.

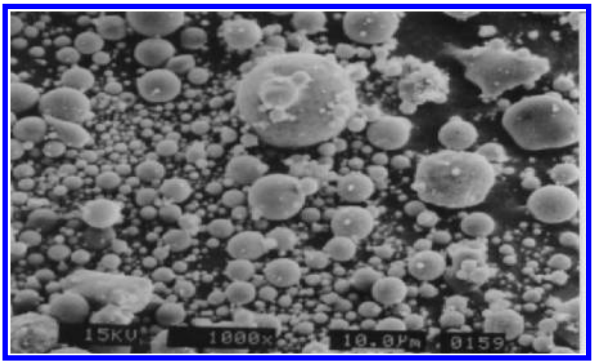

FIGURE 12.2 Fly ash particles, 1000× magnification.

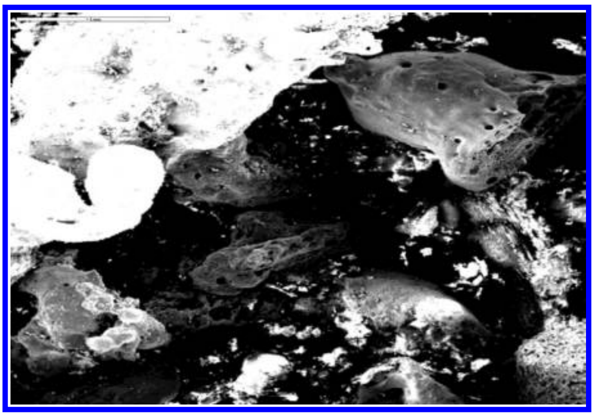

FIGURE 12.3 Bottom ash, 20× magnification.

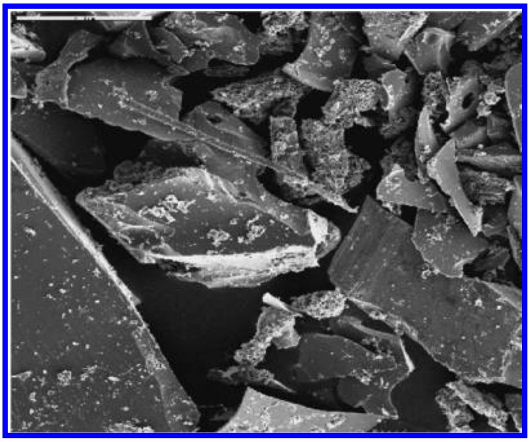

FIGURE 12.4 Cyclone boiler slag, 100× magnification.

(FBC) or flue gas desulfurization (FGD) material produced at coal-fired plants. Coal-fired plants use either pulverized coal-fired furnaces or cyclone furnaces. The cyclone furnaces burn relatively coarse coal particles at a very high temperature, whereas the pulverized, coal-fired furnaces use fine coal particles. During the process of combustion in pulverized coal-fired furnaces, the volatile matters and carbon burn off, and the coal impurities (mostly inorganic materials) fuse and remain in suspension in the boiler. These fused substances solidify when the flue gas reaches a low-temperature zone to form predominantly spherical particles called fly ash. Fly ash is a heterogeneous mixture of particles varying in shape, size (less than 1 μm to more than 1 mm), and chemical composition depending on a variety of factors that include coal's mineral composition, furnace type, type end fineness of the coal, etc. The nitrogen adsorption surface area of fly ash varies in the range of 300 to 500 m^2/kg. Some of these ash matters agglomerate and settle down, and are often quenched in water, at the bottom of the furnace. Such particles are called bottom ash. The pulverized coal-fired furnaces employ either a dry or wet bottom to collect the bottom ash. The amount of bottom ash ranges from 10% to 25% of the total coal combustion by-products. Fly ash constitutes a major component (75%–90%) of the by-product material in pulverized coal-fired power plants. The combustion of coal in cyclone furnaces occurs by continuous swirling in a high-intensity heat zone.[6,7] This causes fusing of fly ash particles into a glassy slag, called boiler slag, which drops to the bottom of the furnace dripping from the side walls of the cyclone boiler. This boiler slag constitutes the major component of the cyclone boiler by-product (70%–85%). The remaining combustion by-products in such boilers exit along with the flue gases. Bottom ash and boiler slag are generally not spherical. They are usually angular and are composed of particles ranging from 2 μm to 30 mm. The bottom ash particles are sometimes round in shape, especially when quenched in water. They generally have a porous structure. Specific gravity for the bottom ash and slag varies between 2.2 and 2.8. Their bulk densities range from 737 to 1586 kg/m^3. The boiler slag is composed of angular particles with a glassy texture. The particle size distribution for fly ash, bottom ash, and boiler slag is given in Figure 12.5.[7,8]

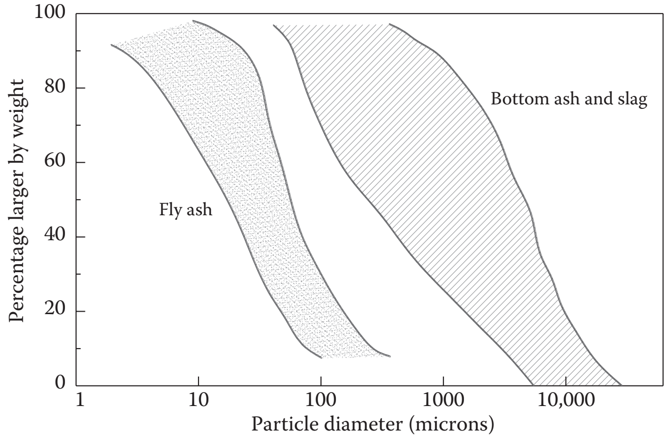

FIGURE 12.5 Particle size distribution for fly ash and bottom ash and slag. (From Naik, T.R. and Chun, Y.-M., International coal combustion products generation and use. *Report No. CBU-2003-34*, Center for By-Products Utilization, University of Wisconsin-Milwaukee, 2003; Summers, K.V. et al., Physical-chemical characteristics of utility-solid waste. *EPRI Report No. EA-3236*, Palo Alto, CA, 1983.)

Clean-coal ash is the ash derived from plants involving the use of SO_x and NO_x control technologies. Coal burning, combined with the pollution control technologies such as low NO_x, FGD, and SO_x control technologies, generates a large amount of CCPs. Wet scrubbers or FGD systems are most commonly used to control power plant SO_x emissions, and they may produce wet or dry by-products.[9] The fly ash amount in FGD material varies from 10% to 50% depending upon whether or not the fly ash was collected prior to the flue gases passing the FGD system. Particle size distribution for the wet-FGD sludge is shown in Figure 12.6.[8]

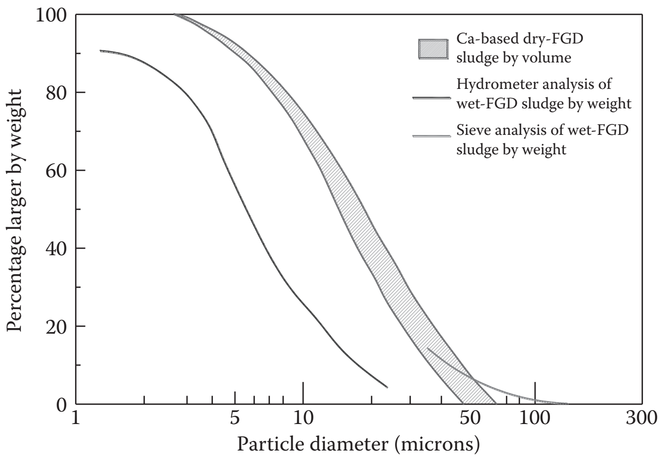

FIGURE 12.6 Particle size distribution for FGD sludge. (From Summers, K.V. et al., Physical-chemical characteristics of utility-solid waste. *EPRI Report No. EA-3236*, Palo Alto, CA, 1983.)

The advanced FGD systems include atmospheric FBC (AFBC) and other FBC systems,[9] lime spray drying, sorbent furnace addition, sodium injection, and other clean-coal technologies such as integrated gasification combined cycle process (IGCC). The solid by-products generated by these processes have some physical and chemical properties that are significantly different from those for conventional coal ashes. Chemical composition of the AFBC and other FBC system residues is given in Table 12.1. The chemical composition of the AFBC fly ash is similar to that of Class

TABLE 12.1
Clean Coal By-Product Chemical Composition in % by Weight

Sample Number	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	SiO_2	Na_2O	SO_3
AFBC								
TVO3 (bed)	2.72	45.07	4.77	0.62	0.31	3.17	0.27	6.50[a]
TVO4 (char)	7.29	30.79	13.20	0.48	0.78	7.97	0.05	20.00
TVO5 (ash)	15.04	22.64	18.88	0.51	1.93	15.26	0.34	17.25
SFO6 (comp.)	6.12	39.13	17.11	0.54	0.72	6.04	0.29	12.00
Spray Dryer								
ARO7	25.20	21.73	3.26	0.84	1.69	21.17	3.29	17.50
STO7	12.60	31.22	10.92	2.93	1.45	15.60	1.76	12.00
LRO7	21.20	26.88	6.11	2.33	0.74	17.72	2.08	12.25
HSO5	24.90	20.02	6.51	2.62	0.75	21.30	1.81	10.25
APO7	24.90	17.67	3.11	0.65	1.35	25.72	2.05	18.25
NVO4	15.00	21.32	4.83	1.53	0.60	20.42	6.58	14.00
RSO5	19.00	28.50	15.34	2.85	0.42	15.96	2.12	13.75
AVO6	18.00	19.03	9.23	4.62	1.46	24.52	9.17	11.50
Lime Furnace Injection (LFI)								
SRO7 (lime)	16.40	28.83	14.20	2.50	2.84	17.72	1.77	12.50
SRO9 (limestone)	17.20	29.15	16.48	0.82	2.96	19.33	1.64	11.25
OLO3 (limestone)	17.80	36.13	13.17	0.63	1.11	15.75	0.48	6.25
OLO4 (limestone)	17.10	40.00	11.91	0.70	1.08	16.18	0.51	5.50
OLO8 (limestone)	29.80	16.80	16.86	0.67	2.12	27.86	1.02	3.50
Calcium Injection								
AHO6	9.07	40.57	2.17	0.56	0.82	10.27	0.59	NA
AA1O-01	31.37	15.39	8.86	1.13	3.37	29.95	1.24	NA
AA1O-02	31.37	13.99	8.86	1.13	3.37	27.81	1.27	NA
Sodium Injection								
NXO4	28.90	4.54	2.50	1.16	0.77	25.18	24.78	12.00
NBO4	30.50	4.40	6.60	0.70	1.45	33.94	12.89	7.75

Source: ICF Northwest, Advanced SO_2 control by-product utilization laboratory evaluation. *PRI Report No. CS-6044*, Palo Alto, CA, 1998.

Note: All elements are expressed as their oxides but may occur in other forms. The designations in column 1 represent sources of test samples.

[a] SO_3 content of the uncrushed sample; the crushed sample had a SO_3 content of 23.9%.

C fly ash, except for SO_3 and SiO_2 contents. The residue of AFBC typically has SO_3 content higher and SiO_2 content lower relative to the conventional Class C fly ash.

The spray dryer by-products (Table 12.1) consist of primarily spherical fly ash particles coated with calcium sulfite/sulfate, fine crystals of calcium sulfite/sulfate, and unreacted sorbent composed of mainly $Ca(OH)_2$ and a minor fraction of calcium carbonate. The spray dryer by-products are higher in concentrations of calcium, sulfur, and hydroxides and lower in concentrations of silicon, aluminum, and iron compared to the conventional Class C fly ash.

The LFI by-products contain 40%–70% fly ash, 15%–30% free lime, and 10%–35% calcium sulfate by weight. The calcium injection process produces by-products (Table 12.1) similar to those of LFI and calcium spray dryer because of the similarities in sorbents and injection methods used. The sodium injection process differs from the calcium injection in regard to the type of sorbent used. The sodium injection process uses a sodium-based sorbent such as sodium bicarbonate, soda ash, trona, or nahcolite.[10] By-products generated by this process include fly ash particles coated and intermixed with sodium sulfite/sulfate and unreacted sorbent. The IGCC process produces by-products similar to the SO_2 control processes. It is evident from the above description that most SO_x control processes generate a by-product similar to the conventional fly ash. But due to the addition of sorbent, the fly ash is modified to a significant extent. The modified fly ash contains fly ash particles coated with sorbent and sorbent reaction products and smaller non-fly ash particles composed of reacted and unreacted sorbents. The solid by-products generated by these processes exhibit some physical and chemical properties that are significantly different than those of conventional coal ashes.[10,11]

12.4.2 Coal-Combustion By-Products and Sustainable Concrete

The use of CCPs in concrete is a proven way since the 1930s to enhance the quality of concrete. The use of CCPs also reduces cost, requirement of virgin materials, and carbon footprint for the production of cement and concrete. In accordance with American Coal Ash Association (ACAA) 2012,[12] the utilization of fly ash in cement and concrete products and blended cement was about 27% of the total fly ash produced. The utilization rate of bottom ash and FGD materials in cement and concrete products and blended cement was about 14% and 7%, respectively. The most widely accepted use of fly ash is in making cement and concrete for reduction of the requirement for virgin raw materials, reduction in cost, and improvement in durability properties.

12.4.2.1 Fly Ash

Fly ash is the largest component of the CCPs produced in the United States. With a view to save a significant amount of energy, requirement of virgin raw materials, and cost in Portland cement manufacturing, as well as in helping to reduce emission of GHGs from the Portland cement production, fly ash is often utilized as a raw-feed material in the production of Portland cement clinker, as well as a major component of blended cements, exceeding 50% of total blended cement mixture.[13,14] Such replacement of cement clinker leads to cements suitable for the manufacture of a sustainable concrete. High volumes of Class C and Class F fly ashes (more than 70% Class C fly ash and up to 60% Class F fly ash as a replacement for Portland cement) have been used to produce high-quality, high-durability concrete pavements with an excellent record of performance.[15,16] ASTM Class C fly ash concrete with low water/cementitious material (w/cm) ratio can be proportioned to meet the very early age strength, as well as other requirements, for precast/prestressed concrete products.[15] The maximum cement replacement with the fly ash for such high-early-strength precast/prestressed concrete applications is at least 30%. Further, fly ash with and without silica fume can be used in the manufacturing of high-performance concrete and self-compacting concrete. It can be used in large amounts as a fine filler material as well as a pozzolan in roller-compacted concrete.[17] Besides its uses as a cement replacement material, as a pozzolan, and as a fine filler material, fly ash can also be used in the manufacture of lightweight aggregates. Both sintered (fired) and unfired (cold-bonded) processing methods can be used.[18,19] Inclusion of fly ash in concrete improves its fresh stage properties such as the workability leading to less energy required for placing of concrete for a better quality of concrete, reduces bleeding and heat of hydration avoiding early-age crack development, and hardened state mechanical and elastic properties, elastic modulus, and impermeability, and reduces thermal conductivity and expansion in comparison with concrete without fly ash.

12.4.2.2 Bottom Ash

Bottom ash could be used as lightweight aggregates for concrete. Large-size bottom ash particles can be used as coarse aggregate, and small-size bottom ash can be used as fine aggregate.[20,21] It can, therefore, be used as a partial replacement for coarse as well as fine aggregates.[22] Some studies[23,24] indicate that bottom ash with pozzolanic ability can also be used for the replacement of Portland cement separately or along with fly ash.

12.4.2.3 Clean-Coal Ash

Relatively less work has been reported for utilization of clean-coal ash and other advanced SO_x by-products. About 7% of the FGD materials are used in cement and concrete.[12] A significant amount of clean-coal ash can be used as a raw material for the production of cement or as a replacement gypsum for the Portland cement product.

One of the most common efforts to make the concrete more sustainable is the use of blended cement in place of conventional Portland cement. The production of blended cement reduces the quantity of cement clinker necessary for the Portland cement. This leads to the result that the quantity of limestone and other raw materials required to produce cement reduces. The reduction in the production of cement clinker results in the reduction of the carbon dioxide and other GHG emissions coming from calcinations of the limestone and combustion of other raw materials in the cement production. Blended cement provides opportunities to reduce the use of natural resources and the emissions of GHGs and to recycle suitable fly ash. However, these potential benefits of blended cement are dependent on the availability of locally available amount and the quality of fly ash. In fact, the potential for CO_2 emission reduction from producing blended cement and use of coal ash in sustainable concrete varies from country to country. Countries without coal-fired power plants have limited potential for using coal ash in the production of concrete containing it.

12.5 FOUNDRY BY-PRODUCTS

Foundry by-products (used foundry sand and slag) result from the metal-molding and core-making processes in the metal casting industry (foundry). Metal casting industries use sand molds to cast metallic materials into desired shapes. Since sand grains do not naturally bond with each other, binders are used to cause sand grains to stick together and retain shape during the introduction of molten metal into the mold. Two types of binder systems, namely, green sand and chemically bonded system, are used in making the mold. Other types of foundry by-products are also generated primarily by melting operations (such as cupola slag) with minor contributions from cleaning of castings and dust collectors. Foundry by-products include used foundry sand, floor sweepings, cupola slag, and dust-collector fines. The commonly used green sand for mold making is composed of four major materials: sand, clay, sand additives, and water. Sand usually constitutes 50%–95% of the total materials in a mold.[25] Clay acts as a binder for the sand. The amount of clay varies from 4% to 10% for the green sand mixture.

Core sands are composed primarily of silica sand with small percentages of either organic- or inorganic-type binders. The organic binders include oil, synthetics, cereal proteins, and other similar binding agents. The inorganic binders usually include Portland cement, fly ash, and sodium silicate. Another important by-product from foundries is cupola slag. Slag, which is primarily composed of metal oxides, is usually removed from the cupola by conditioning them through the use of fluxes or flocculants. The fluxes used include fluorspar, limestone, and soda ash. Silica is also one of the flocculants used. The furnaces, or cupolas, emit exhausts carrying suspended dust particles, which are captured by particulate collection systems such as a baghouse or wet scrubbers. These particulate matters are designated cupola dust.

Depending on the binder systems used, the sand from a foundry has different physical and chemical characteristics. The properties of the used foundry sand vary due to factors such as the type of the foundry processing equipment used, the types of additives used for mold making, the number of times the sand is recycled and reused in mold making, and the type and amount of the binder used.[26] The sieve analysis results for a typical regular concrete sand, clean foundry sand, and used foundry sand are shown in Figure 12.7. Used foundry sand can be utilized as a replacement for regular concrete sand. A 30% replacement of regular concrete sand with used foundry sand resulted in a grading curve for the composite sand material that is very close to the upper limit of ASTM C-33 (Figure 12.8)[27] for regular concrete sand. The physical properties of the regular concrete sand, clean foundry sand, and used foundry sand are presented in Table 12.2. The results reveal that the used foundry sand is much finer than the concrete sand and does not fall within the ASTM C-33 limits. Used foundry sands also have higher unit weight compared to regular concrete sand.[27] The used foundry sand is composed of metallic elements in addition to silica, which is also found in regular concrete sand. Used foundry sand particles are weaker than regular concrete sand particles because they are subjected to a complex form of heating and cooling temperature loads. Oxide analysis of a used foundry sand by American Foundrymen's Society[28] shows SiO_2 (87.9%), Al_2O_3 (4.7%), Fe_2O_3 (0.9%), CaO (0.1%), MgO (0.3%), SO_3 (0.1%), N_2O (0.2%), K_2O (0.3%), TiO_2 (0.2%), and loss on ignition (LOI; 5.2%).

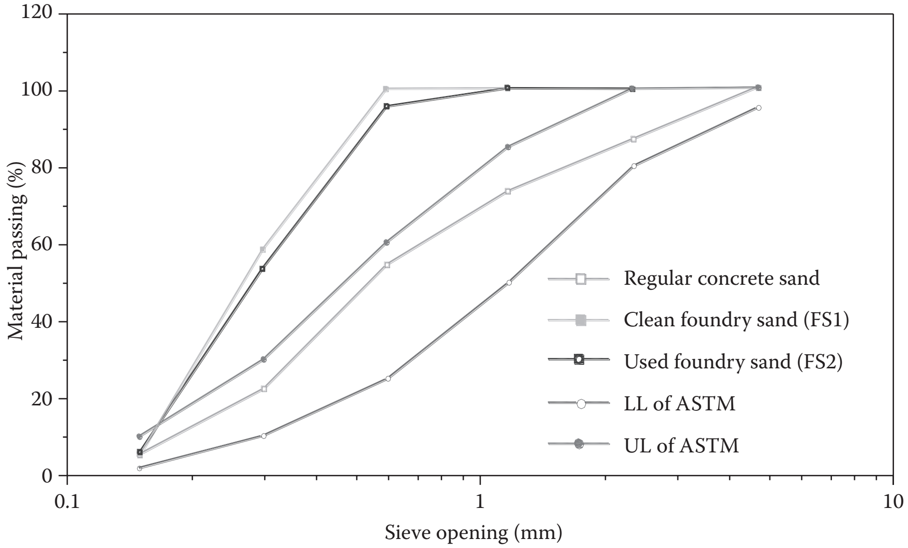

FIGURE 12.7 Sieve analysis envelope for regular concrete sand and foundry sands. (From American Foundrymen's Society (AFS) Inc., Alternate utilization of foundry waste sand. *A Report to Illinois Department of Commerce and Community Affairs*, Des Plaines, IL, 1991.)

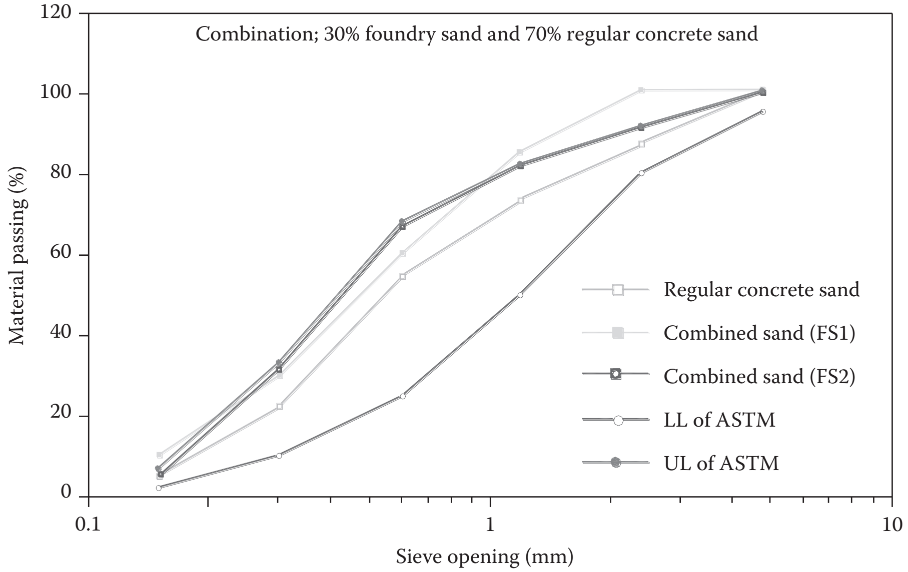

FIGURE 12.8 Sieve analysis envelope for foundry sand combined with regular concrete sand. (From American Foundrymen's Society (AFS) Inc., Alternate utilization of foundry waste sand. *A Report to Illinois Department of Commerce and Community Affairs*, Des Plaines, IL, 1991.)

TABLE 12.2
Physical Properties of Sand

	As Received Moisture Content, %	Unit Weight, kg/m³	Bulk Specific Gravity	Bulk Specific Gravity, SSD	Apparent Specific Gravity	SSD Absorption,%	Void,%	Fineness Modulus	Clay Lumps and Friable Particles, %	Soundness of Aggregates, %	Material Finer than #200 (75 μm) Sieve
ASTM	**C 566**	**C 29**	**C 128**				**C 29**	**C 136**	**C 136**	**C 88**	**C 117**
Sand 1	0.39	1840	2.43	2.47	2.52	1.0	25.0	3.57	0.2	10.0	1.40
Sand 2	0.19	1730	2.38	2.50	2.70	4.9	33.8	2.33	0.1	54.9	0.17
Sand 3	0.25	1784	2.44	2.57	2.79	5.0	34.8	2.32	0.4	10.5	1.08

Source: American Foundrymen's Society (AFS) Inc., Alternate utilization of foundry waste sand. *A Report to Illinois Department of Commerce and Community Affairs*, Des Plaines, IL, 1991.

Note: Sand 1—regular concrete sand; Sand 2—clean foundry sand (FS1); Sand 3—used foundry sand (FS2).

12.5.1 Foundry Sands

The use of high-quality silica sand in foundry industry makes the used foundry sand by-product an excellent material for the manufacturing of Portland cement, concrete, and concrete products.[28–32] Therefore, used foundry sand is utilized as a replacement for sand in the production of concrete; it has the potential to reduce mining of new sand. Several studies[27–34] have shown that foundry sand can be used in concrete as a replacement for regular concrete sand at least up to 35% by weight to meet strength requirements for structural-grade concrete. The slump (workability) of concrete containing used foundry sand reduces with the increase in the replacement level of regular concrete sand with foundry sand. The reduction in the slump value is attributed to the increase in the specific surface area of the finer foundry sand and to the presence of a binder, such as clay, that increases the water demand.

The hardened properties of concrete containing used foundry sand such as compressive and tensile strengths could be lower than control concrete without used foundry sand. This decrease in strength depends on the replacement level of sand by foundry sand. Naik[27] studied the performance of concrete containing foundry sand in place of fine aggregate and evaluated the compressive strength, tensile strength, and modulus of elasticity of the concrete with respect to reference concrete containing regular sand as fine aggregate. The regular sand was replaced by used foundry sand (mixtures 20-F2 and 20-F3) up to 35% by weight of the regular concrete sand. The results of 28-day compressive strength, tensile strength, and modulus of elasticity of the concrete mixtures are shown in Table 12.3.

Based on their study, Naik[27] concluded that structural-grade concrete could be manufactured by using used foundry sand as a replacement of at least up to 35% of regular concrete sand. They further showed that concrete containing 35% used foundry sand developed about 10% less compressive strength than the concrete containing 25% foundry sand. The test results showed some reduction in concrete strength due to the utilization of used foundry sand, which was probably due to the presence of clay binders in it. But Domann[35] has shown that this loss in strength could be compensated by a judicious mixture proportioning using Class C fly ash in the concrete containing used foundry sand.

TABLE 12.3
28-Day Compressive Strength, Tensile Strength, and Modulus of Elasticity of Concrete

Mixture Number	20-F1 0%	20-F2 25%	20-F3 35%
Compressive strength, MPa	43.8	33.6	30.7
Tensile strength, MPa	4.6	3.6	3.1
Modulus of elasticity, GPa	31.7	31.7	32.6

Source: Naik, T.R., Foundry industry by-products utilization. *Report No. CBU-1989-01*, Center for By-Products Utilization, University of Wisconsin-Milwaukee, 1989.

TABLE 12.4
Compressive Strength and Modulus of Elasticity of Concrete

Mixture Number	Mixture 1	Mixture 2	Mixture 3
Specified design strength, MPa	42	42	42
Foundry slag, %	0	50	100
Compressive strength, MPa	46	38	40
Modulus of elasticity, GPa	36	31	41

Source: Edey, D.C. and Winter, W.P., *Introduction to Foundry Technology*. McGraw-Hill Book Company, New York, 1958.

12.5.2 Foundry Cupola Slag

Foundry cupola slag is a glass-like amorphous material obtained from the melting furnace/cupola of iron foundries.[35] Foundry cupola slag is appropriately used as a coarse, semi-lightweight aggregate for use in cement-based materials.[26] Naik et al.[27,28] also demonstrated that foundry cupola slag could be used as a replacement of normal-weight aggregate (50%–100% replacement range) in the manufacture of structural-grade concrete. They evaluated the performance characteristics of concrete containing foundry cupola slag compared with a control concrete mixture targeted for a compressive strength of 42 MPa at 28 days. They used one control concrete mixture without foundry slag, and two other concrete mixtures contained 50% and 100% foundry slag as a replacement of the regular aggregate. The compressive strength and modulus of elasticity of the concrete at 28 days are given in Table 12.4.

They found that concrete containing 100% slag developed compressive strength comparable to the control concrete. However, the modulus of elasticity of concrete containing 100% slag was higher than that of the control concrete. The study suggested that foundry cupola slag could be used as a replacement of normal-weight aggregate in the manufacture of sustainable concrete. Recently, two buildings were constructed in Milwaukee, Wisconsin, by using foundry sand in combination with fly ash to achieve the economic and environmental benefits.[36] They showed the potential use of this material in the manufacture of a sustainable concrete.

12.6 PULP AND PAPER INDUSTRY BY-PRODUCTS

Pulp and paper mill by-products are mainly sludge from liquid waste treatment plants. This sludge, residual solids from the liquid waste treatment plants, is primarily composed of very short cellulose fibers; ash-bearing inorganic compounds; and minerals (such as clay, limestone, TiO_2, etc.), lignin-based chemicals, and moisture. The residual solids are generally placed in lagoons, landfilled, or applied to land for cultivation.[37,38] Solids are removed at the primary clarifier by sedimentation or dissolved air flotation. The solid content of such residuals after mechanical dewatering is typically 30%–40% by weight.[39] The chemical composition of a typical residual consists of moisture (70%), solids (2%), ash (7.8%), calcium (2670 ppm), iron (1280 ppm), nitrogen (740 ppm),

TABLE 12.5
Chemical Composition of Primary Residuals

Constituents	Value
CaO	0.55–31.46
SiO_2	9.29–21.78
Al_2O_3	3.37–19.13
MgO	0.2–1.7
TiO_2	0.04–4.62
LOI	55.4–83.4

Source: Thomas, C.E. et al., *ASCE Journal of Environmental Engineering*, Vol. 113, No. 1, pp. 16–31, 1987.

kjeldahl nitrogen (sum of organic and ammonia nitrogen) (740 ppm), magnesium (234 ppm), chloride (185 ppm), zinc (170 ppm), phosphorus (102 ppm), potassium (20 ppm), sulfur (15 ppm), organic carbons (12.0%), copper (7.0 ppm), lead (5.3 ppm), molybdenum (4.2 ppm), chromium (4.2 ppm), manganese (3.0 ppm), polychlorinated biphenyls (PCB) (2.5 ppm), nickel (1.1 ppm), boron (0.5 ppm), and mercury (0.1 ppm),[39] and Table 12.5 presents a typical chemical composition of primary residuals.[40]

12.6.1 Use of Pulp and Paper Industry Residual Solids

Pulp and paper mill residual solids can be used as an additive in cement manufacture (or as a new source of pozzolan from de-ink solids) and to produce concrete.[41,42] Pera and Ambroise[43] have reported that when the pulp and paper mill sludge are calcined at about 700°C, then these residuals show pozzolanic properties that could be used in the development of high-strength and/or colored concrete. Further, calcinations of the residual at over 750°C result in a self-cementing material that could be used to replace Portland cement. An extensive study carried out by Naik[44] on the strength and durability of concrete containing residual solids from pulp and paper mills has revealed that the addition of residual solids in concrete enhances its durability properties in freezing and thawing environment. It was also revealed that the addition of residual solids reduces the chloride-ion penetrability of concrete and enhances the salt-scaling and freezing and thawing resistance of concrete, thereby showing its potential for use in the manufacture of sustainable concrete.

The possibility of producing good-quality lightweight aggregates using paper mill sludge has also been reported.[44,45] A study showed that a blend of bark ash (8%) and Class F ash (92%) could be used as a replacement for 20% Portland cement.[46] In a recent study,[47,48] paper mill ash in the form of fine powder with maximum grain size smaller than 1 mm was used in producing blended cements by replacing 10% and 20% of cement for assessing its potential as secondary raw materials for blended cements. The results obtained for compressive strength showed a promising potential for its use. Further, they used the paper mill ash as very fine sand addition to low-fine aggregates in concrete. Four such concrete mixtures were used, two of which by using a natural aggregate with suitable grain size distribution while the other two by adding ash to correct the grain size distribution of a natural aggregate poor in the finer fractions (63–300 μm). Concrete mixtures were prepared with water/cement ratios of 0.60 and 0.45. A workability loss due to ash addition was noticed. However, insignificant influence on the development of compressive strength with respect to time was noted for the concrete containing paper mill ash, indicating a potential to be used in the production of concrete of 28-day strength ranging from 35 to 65 MPa.[48] Therefore, pulp and paper mill by-products can be used as a replacement for sand, as a secondary raw material for blended cement, as a replacement for cement, and in the manufacturing of coarse aggregate for use in sustainable concrete.

12.7 WASHED WATER FROM READY-MIXED CONCRETE PLANTS

Water is an important ingredient of concrete as it actively participates in reaction with cement. Potable water is commonly used to make and cure concrete. Worldwide, about 190 L of water per person is used in the production of concrete.[49] Potable water is becoming scarcer and/or more expensive to meet the daily needs of human activities. Therefore, such a large amount of portable water cannot be continued to be consumed in concrete-related activities. Ready-mixed concrete plants produce a large amount of waste wash water, the disposal of which has many adverse environmental impacts. Such water has many useful suspended solids. It also has a high pH. Therefore, partial and complete recycling of waste wash water in concrete manufacturing should prove a positive step toward sustainable concrete. Several research studies[50–54] have suggested partial replacement of potable water in concrete with waste wash water of ready-mixed concrete plants without a significant compromise of desirable mechanical and durability properties of concrete. In addition to mixing in concrete, Tay and Yip[53] have also suggested using such reclaimed water for the curing of concrete.

12.8 POSTCONSUMER MATERIALS IN SUSTAINABLE CONCRETE SYSTEM

12.8.1 Used Tires

Stockpiled used tires (Figure 12.9) create a desirable environment for breeding mosquitoes and a habitat for rodents and vermin. Currently, landfills in many states of the United States restrict the burial of whole tires in municipal landfills due to several factors, including the following: tires are not biodegradable and cannot be easily compacted, resulting in more space requirements, and they “float up” to the surface

FIGURE 12.9 Stockpiled scrap tires.

due to settlement of other materials surrounding it and the buoyancy effects of gases trapped by the tires. This, in turn, exposes landfill to insects, rodents, vermin, and scavenger birds. Used tires must be shredded before landfilling.

According to the Industrial Resources Council,[55] about half of the annually generated used tires are utilized as a combustion fuel using new technologies having pollution control equipment. Tire-derived fuel is popular as the energy provided by the burning of tires is comparable to that of oil and greater than that of coal. Tires are low in sulfur and have low NO_x gas emissions and can produce a cleaner ash than coal. By using controlled combustion environment of cement kilns, used tires are being utilized as an environmentally sound source of energy for the manufacturing of cement. About 4% of used tires were recycled through the use of ground rubber, whereas about 6% were re-treaded in 2003.[57] Even with all these reuse and recycling efforts each year, over 9% of used tires are disposed of in landfills or monofills.[57]

The raw materials in tires include natural and synthetic rubber; carbon black; steel; nylon; polyester; and even Kevlar cord, sulfur, oils and resins, and other chemicals.[58] Tire rubber with fiber and steel belting comprise the major elements of tires currently being used. Of all the possible methods of tire disposal, the creation of rubber crumb potentially offers the most effective environmental solution because this is the material that can be used in a variety of other products. Tire rubber is ground to a particulate form termed as crumb rubber modifier (CRM). Crumb rubber consists of particles ranging in size from 4.75 mm (no. 4 sieve) to less than 0.075 mm (no. 200 sieve). The composition of CRM depends greatly upon the original chemistry of the tire rubber and subsequent contamination during its use. Tires can be used for environmentally safe applications in whole, cut, or stamped form in civil engineering works such as highway crash barriers, sound-absorbing walls, boat benders on harbor walls,[59] insulation in building foundations, and road base materials[60] besides in Portland cement concrete.

12.8.1.1 Used Tires in Sustainable Concrete

Tire chips (Figure 12.10) and CRM (Figure 12.11) can be used in concrete as a partial replacement of aggregate,[61–76] with or without surface treatment. In several studies,[61–76] the rubber surface was subjected to chemical pretreatment to reinforce adhesion of the rubber with the cement matrix for obtaining an improvement of some properties of the concrete.

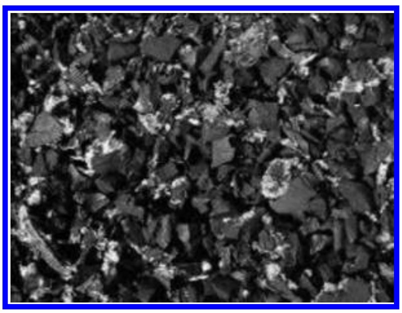

FIGURE 12.10 Coarse aggregate from used tire.

FIGURE 12.11 Crumbed rubber aggregate.

The effects of aggregate substitution by tire chips or crumb rubber on the slump/workability and unit weight of concrete have been reported by several researchers.[61–63,66,67,69,71–74] The tire chips are used to substitute a portion of coarse aggregate, whereas crumb rubber granules are used to substitute sand. Eldin and Senouci[61] have reported an increase in harshness or a decrease in workability with an increase in the maximum size or percentage of rubber chips used for the substitution of coarse aggregate in the concrete mixture. They further reported insignificant change in the slump for the replacement of sand by crumb rubber up to 25%, but, at higher replacement levels, a greater reduction in workability was observed. Toutanji[77] found a reducing trend for concrete slump with an increase in the volume of substitution of coarse aggregate with shredded rubber tires in the mixtures. Contrary to observations as mentioned earlier, Raghvan et al.[73] have reported that mortars incorporating rubber shreds achieved workability comparable to or better than a control mortar without rubber particles. Khatib and Bayomy[70] investigated the workability of "rubcrete" and have reported that there is a decrease in slump with an increase in rubber content by total aggregate volume. They have further reported that at rubber contents of 40% by total aggregate volume, slump was almost zero, and concrete was not workable manually. They also observed that mixtures made with fine crumb rubber were more workable than those with coarse tire chips or a combination of tire chips and crumb rubber.

A reduction in the unit weight of concrete is generally encountered when aggregate is replaced by rubber. This reduction is mainly due to the lower unit weight of tire's rubber compared to mineral aggregate. A smaller reduction in the unit weight compared to that of coarse aggregate replacement was found when sand was replaced by crumb rubber (1-mm maximum size). This is due to the lower volume of sand in the concrete compared to the coarse aggregate. Moreover, an increase in rubber content also increases the air content, which in turn reduces the unit weight of the concrete mixtures. The decrease in the unit weight of rubcrete is negligible when the rubber content is lower than 10%–20% of the total aggregate volume. Higher air content in rubcrete mixtures than control mixtures even without the use of air-entraining admixture is commonly noted.[68,70] This is attributed to the nonpolar nature of rubber particles and their tendency to entrap air in their rough surface and the tendency of rubber particles to repel water. Therefore, an increase in the tire rubber content in concrete results in higher air contents of concrete mixtures.

In general, there is a reduction in the slump value of the concrete mixtures with the increase in the maximum size of the tire chips or with the increase in the percentage of volume of coarse aggregate replaced. The reduction in the slump due to the replacement of concrete sand by CRM is not significant.

Most of the studies have indicated that the use of tire chips and CRM causes a significant reduction in concrete compressive strength due to the poor bond between the tire as aggregates and the cementitious matrix. The compressive strength of concrete mixtures is greatly affected by the size, proportions, and surface texture of rubber particles and the type of cement used in such mixtures. Up to 85% reduction in compressive strength and 50% reduction in split tensile strength when coarse aggregate was fully replaced by rubber chips have also been reported.[62] A reduction in compressive strength up to 65% and split tensile strength up to 50% was observed when fine aggregate was fully replaced by fine crumb rubber.[62] But the mixtures demonstrated a ductile failure and had the ability to absorb a large amount of plastic energy under compressive and tensile loads. Similar observations were also reported by others[67,75] where the addition of coarse rubber chips in concrete lowered the compressive strength more than the addition of fine crumb rubber. The possible reasons for the reduction in strength include lack of adhesion between rubber particles and the cement paste and much softer particles of rubber than the surrounding cement paste. Therefore, under stressed conditions, cracks are initiated quickly around the rubber particles that accelerate the failure of the rubber–cement matrix. The decrease in mechanical properties (compressive, splitting tensile, and flexural strength) is found to be directly proportional to the quantity of the rubber content. Also, the size of the rubber crumbs appears to have an influence on strength. Coarse grading of rubber crumbs lowers compressive strength more than finer grading. The addition of tire rubber is also found to soften the elastic stress–strain response, yielding Young's moduli as low as 10,000 MPa.[68,77–79]

In spite of the fact that the mechanical properties of concrete are downgraded by the presence of crumb rubber, there remain many other properties of concrete that benefit from the use of crumb rubber, such as freeze–thaw durability,[80] mass density reduction of concrete,[62,68,70,81] nonstructural crack resistance property,[82] and improved ductile behavior with capability of absorbing a large amount of energy under compressive and flexural loads.[81] The limitation of reduction in the mechanical properties of concrete containing scrapped tire can be overcome by the use of technology such as use of magnesium oxychloride cement[76] and through the use of micro-fine CRM in cement-based materials.[83] Such technology, however, would increase the cost of the concrete. Therefore, further research is needed in order to find specific mixtures that would be able to limit the strength loss.

12.9 POSTCONSUMER PLASTICS IN SUSTAINABLE CONCRETE

Plastics have become an unavoidable component of our day-to-day life. The global use of plastics is increasing day by day and ending up in a substantial portion of postconsumer waste. In 2011, postconsumer plastics contributed almost 32 million tonnes to municipal solid wastes (MSWs) in the United States.[84] The amount of plastic in MSW has increased from 1% in 1962 to 13% in 2011. The recycling rate for different types of plastic varies greatly, resulting in an overall plastic recycling rate of only 8% in 2011. About 29% of high-density polyethylene (HDPE) bottles and 29% of polyethylene terephthalate (PET) bottles and jars were recycled in 2011 in the United States.[84] Plastics can be divided into two major categories: thermosets and thermoplastics. A thermoset is a polymer that sets irreversibly when heated. They are useful for their strength and durability, and, therefore, they are used mainly in automobiles and construction applications. On the other hand, a thermoplastic is a polymer in which the molecules are held together by weak bonds, creating plastics that soften when exposed to heat. Thermoplastics can easily be shaped and molded into products such as milk jugs, soda bottles, carpet fibers, and many other similar products. There are seven types of plastics: (1) PET, commonly found in soft drink bottles, is the number one recycled resin; (2) HDPE, the second most commonly recycled resin, is found in milk jugs and base cups of soft drink bottles; (3) polystyrene is commonly used in egg cartons, plates, cups, and packaging “peanuts”; (4) low-density polyethylene (LDPE) is generally found in films and trash bags; (5) polypropylene is generally used in hard casings of luggage and battery castings; (6) polyvinyl chloride is used in flooring, piping, wiring, and other similar uses; and (7) linear LDPE.[85]

12.9.1 Recycling of Postconsumer Plastics

Compared with other postconsumer materials like glass, metals, tires, etc., plastic polymers require greater processing to be recycled. It is difficult and uneconomical to recycle all plastic wastes. The most widely recycled postconsumer plastic waste is PET, commonly found in soft drink bottles, followed by HDPE, found in milk jugs and base cups of soft drink bottles. Recycled plastic is generally used to produce resin, fibers, and aggregate to be used in concrete for the manufacturing of specific products.

In the past, many attempts have been made to use recycled postconsumer plastic derivatives[86–97] such as resin as an alternate binder, aggregates, and fibers (particulate filler) in cement concrete. Earlier studies for the use of resin reclaimed from PET derived from soda bottles in the manufacturing of polymer concrete (PC) system were carried out by Rebiez et al.[88,89] For this purpose, the PET material was processed to produce a liquid resin using the facilities available at a commercial company. This process is not available for other types of plastic and is not considered economically feasible at the present time. For the investigations reported, unsaturated polyester resins were obtained from several commercial sources. Each contained a particular percentage of recycled PET. The amount of recycled PET varied between 15% and 40%. These resins were prepolymers with high viscosities (100 to 1890 cps). Styrene was added to reduce the viscosity of the resins. Appropriate initiators and promoters were then added to the resins immediately prior to the mixing with concrete aggregates in order to initiate and accelerate polymerization (curing or hardening of the resin to a solid plastic state). For the manufacture of PC, the resin and aggregate were mixed in a conventional concrete mixer for approximately 3 min, and then the specimens were cast, vibrated, and allowed to cure at room temperature for 3 to 9 days prior to testing. In general, they concluded that the inclusion of recycled PET did not have detrimental effects on the PC.

Use of postconsumer plastics as a flexible particulate filler in concrete should improve its fracture toughness. However, due to the absence of a chemical bond between the plastic filler and the cementitious matrix, the potential increase in toughness is generally not achieved. To solve this problem, Naik et al.[86,87] introduced a chemical bond between the plastic particles and the cementitious matrix using chemical treatments. They carried out an extensive experimental study for the use of postconsumer waste HDPE plastic in concrete. The plastic particles were added to the concrete in the range of 0%–5% of the total mixture by weight. In order to increase the bonding between the plastic particles and the concrete matrix, the plastic particles were subjected to three chemical treatments (water, bleach, bleach + NaOH). The compressive strengths of the concrete with and without plastic particles were evaluated. All concrete mixtures developed lower compressive strength than the reference concrete; however, the mixture containing plastic treated with bleach + NaOH performed the best, followed by the water-treated plastic sample. The results (Table 12.6) of concrete containing plastic (ranging 0%–2%) treated with water showed that 0.5% of plastic could be used in concrete without compromising the compressive strength.

Beyond 0.5% addition of plastic particles by the weight of the concrete, concrete strength decreased. They recommended that plastic should be processed to obtain high aspect ratios for improving the performance of the plastic filler due to its increased bond area and load transfer capability. They finally demonstrated that the chemical treatment, alkaline bleach treatment (bleach + NaOH), on plastic had a significant effect on performance with respect to compressive strength and tensile strength development of the concrete in which it was used.

Generally, the slump of concrete containing plastic aggregate is higher than conventional concrete due to its non-absorptive characteristics. The unit weight of concrete containing postconsumer plastic waste is lower than the conventional concrete. The mechanical properties such as compressive strength, modulus of elasticity, tensile strength, etc., of concrete containing plastic aggregate derived from postconsumer plastic wastes decrease with the increase in the aggregate content. However, better structural efficiency (lightweight concrete) and toughness durability are some beneficial properties that make use of recycled products derived from waste plastic such as resin, aggregates, and fiber for the manufacturing of various precast products such as sewer pipes, underground vaults, drain, power line transmission poles, median barriers of roads, repair materials, etc. As a fine aggregate, PET wastes may be used for the development of lightweight aggregate concrete; the compressive strength of such concrete may be reduced by 5%–30% depending upon its quantity in

TABLE 12.6
Effect of Water-Treated Plastic Content on Compressive Strength of Concrete

Mixture No.	P 0 (0% Plastic)	P 0 (0.5% Plastic)	P 0 (1.5% Plastic)	P 0 (2% Plastic)
28-day compressive strength, MPa	28.1	28.3	21.7	14.8

Source: Naik, T.R. et al., *Cement and Concrete Research*, Vol. 26, No. 10, pp. 1482–1489, 1996.

the concrete mixture. However, the structural efficiency, i.e., compressive strength/density of such concrete, is higher than conventional concrete.[96]

12.10 POSTCONSUMER GLASS IN SUSTAINABLE CONCRETE

According to the US Environmental Protection Agency, approximately 11.5 million tons of postconsumer glass was generated in the United States in 2011.[98] Glass consists primarily of silica or fused silica sand and smaller amounts of lime sand and soda ash.[99] Three types of glass, namely, borosilicate, soda lime, and lead glass, are manufactured. The majority of glasses manufactured in the United States are of the soda lime variety. The chemical compositions of these types of glasses are presented in Table 12.7.

Crushed glass exhibits properties of an aggregate material. Postconsumer glass after crushing can be used as a coarse or fine aggregate for partial replacement of aggregates.[101–115] It can also be used as a partial replacement of cement[116,117] in concrete. Topcu and Canbaz[107] used crushed glass of 4–16 mm for partial replacement of coarse aggregate (15%, 30%, 45%, and 60%) and reported insignificant reduction in slump and unit weight of concrete containing glass aggregate in comparison with of concrete without glass aggregate. Terro[108] studied the effect of replacement of fine and coarse aggregates on the slump of concrete with recycled glass aggregates and reported an increase in the slump value with higher percentage of waste glass aggregates. He attributed the increase in slump of concrete to the lower specific surface and smooth surface of the coarse glass aggregate that could have reduced the interparticle friction. On the other hand, Park et al.[106] reported a sharp reduction in the slump of concrete containing crushed glass as fine aggregate at replacement levels of 30%, 50%, and 70% of sand. They held a sharper and more angular grain shape of crushed aggregate responsible for the reduction in the slump of concrete.

Ducman et al.[109] reported the manufacturing of expanded glass aggregate (lightweight aggregate) by using finely ground postconsumer glass with a suitable

TABLE 12.7
Chemical Composition of Glass

Constituent	Borosilicate	Soda Lime	Lead
SiO_2	81	73	63
R_2O_3	2	1	1
Na_2O	4	17	7
K_2O	–	–	7
B_2O_3	13	Trace	–
CaO	–	5	–
MgO	–	3	–
PbO	–	–	22

Source: Miller, R.H. and Collins, R.J., Waste materials as potential replacements for highway aggregates. *NCHRP Report No. 166*, TRB, NRC, Washington, DC, 1976.

expanding agent and firing this mixture at a temperature above the softening point of the glass. They further reported that the aggregate was highly reactive with Portland cement because it was an additional source of alkalis. Expansion or cracks due to the possibility of alkali–silica reaction (ASR) were a concern but were not observed in the mortar bar even after 284 days. This was attributed to the porous structure of the lightweight aggregates made from the glass. For glassy aggregates, the possibility of ASR could not be ruled out especially in the case of aggregate based on postconsumer glass, which may contain reactive silica. The combination of high silica content and the amorphous structure of the glass as an aggregate is potentially deleterious and may react and create expansion with even a low level of alkalis present in the cement.[110]

Various researchers[102–105,109] have reported that the glass could activate ASR in cement-based materials. The resulting expansion due to ASR causes reduction in strength and has a highly negative impact on durability. Thus, the use of glass as an aggregate in cement-based materials is dependent upon resolving the problem associated with ASR.[111,112] There are several ways to solve ASR problems in cement-based materials. The most commonly used method is to add a pozzolanic material such as fly ash, silica fume, or ground granulated blast furnace slag.[105,111,113] Other methods include the use of chemical ASR inhibitors such as lithium compounds.[113] These investigations have described other methods such as grinding glass to very fine sized particles (passing no. 200 mesh sieve, i.e., 0.075 mm), treating glass with LiOH, or curing concrete with CO_2 to suppress ASR reaction. Meyer et al.[111,112] reported that grinding of the glass to very small size particles (finer than 300 μm) is the most promising way to combat the ASR expansion due to the presence of silica in the postconsumer glass. Such grinding is not popular because it is not cost effective. Research by Polley et al.[114] demonstrated that concrete containing glass as a sand replacement can display a greater degree of expansion due to ASR. However, this problem can be avoided by the inclusion of a pozzolan. A comparative study on the potential of ASR created by the glass aggregate used in Portland cement mortar and in water–glass-activated fly ash (WAFA) mixtures by Xie et al.[115] reported less ASR expansion in the WAFA mortar, even up to 100% of replacement of aggregates by the glass aggregate. Their study also did not report the effect of the color of the glass on the WAFA mortar.

Naik and Wu[105] studied the feasibility of using crushed postconsumer glass as a partial replacement of sand in concrete. A source of Class F fly ash was also used in the study to suppress the deleterious reaction between the alkali in cement and the silica in crushed postconsumer glass (ASR). For each combination of cement and fly ash, 15%, 30%, and 45% volumes of SSD sand were replaced with crushed glass. The compressive strength, splitting tensile strength, and ASR were evaluated for the concrete mixtures (Table 12.8). Test results are given in Figures 12.12, 12.13, and 12.14. They indicate that both compressive and splitting tensile strengths of concrete decreased slightly with an increase in the replacement rate of the sand with the crushed glass. Similar results were reported by Park et al.[106] and Topcu and Canbaz.[107] The decrease in strength is attributed to the decrease in adhesion between cement paste and the postconsumer glass aggregate.

Naik and Wu[105] further reported that when Class F fly ash was used as a replacement for cement, then at lower replacement rates (at 30% or less), Class F fly ash

TABLE 12.8
Concrete Mixture Details for the Replacement of Sand with Crushed Glass

	Quantities, kg/m³															
Mixture Number	**A0**	**A1**	**A2**	**A3**	**B0**	**B1**	**B2**	**B3**	**C0**	**C1**	**C2**	**C3**	**D0**	**D1**	**D2**	**D3**
Cement	429	427	426	421	362	361	361	359	298	296	298	298	234	232	232	231
Fly ash	0	0	0	0	79	79	79	79	160	160	160	161	240	237	237	236
Sand	720	611	499	389	677	574	477	375	642	548	444	346	607	507	406	304
Glass	0	99	197	292	0	98	196	295	0	97	195	293	0	97	193	291
Stone	1079	1073	1071	1059	1073	1071	1071	1067	1069	1064	1070	1072	1073	1064	1064	1059
Water	178	173	174	176	179	178	177	177	177	174	171	173	174	174	175	175
w/cm	0.42	0.41	0.41	0.42	0.41	0.41	0.40	0.40	0.39	0.38	0.37	0.38	0.37	0.37	0.37	0.37
Unit weight, kg/m³	2406	2384	2367	2337	2371	2363	2362	2353	2346	2338	2337	2343	2329	2312	2308	2295
Slump, mm	85	70	65	70	65	85	45	55	90	90	75	70	85	90	75	75
Air content, %	1.4	1.8	1.8	2	1.4	1.3	1.4	1.5	1.1	1.1	1.4	1.5	1.3	1.6	1.4	1.6

Source: From Naik, T.R., and Wu, Z., Crushed post-consumer glass as a partial replacement of sand in concrete, *Report No. CBU-2000-17*, Center for By-Products Utilization, University of Wisconsin-Milwaukee, 2000.

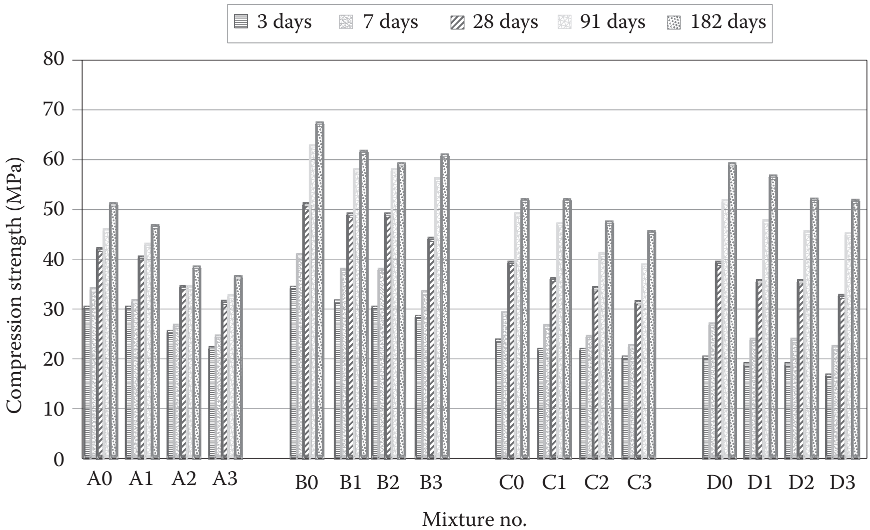

FIGURE 12.12 Compressive strength development of concrete mixtures for replacement of sand with crushed glass. A0, A1, A2, and A3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume), respectively. B0, B1, B2, and B3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume) and 15% cement replaced with Class C fly ash by mass on replacement level of 1:1.25, respectively. C0, C1, C2, and C3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume) and 30% cement replaced with Class C fly ash by mass on replacement level of 1:1.25, respectively. D0, D1, D2, and D3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume) and 45% cement replaced with Class C fly ash by mass on replacement level of 1:1.25, respectively. (From Naik, T.R., and Wu, Z., Crushed post-consumer glass as a partial replacement of sand in concrete, *Report No. CBU-2000-17*, Center for By-Products Utilization, University of Wisconsin-Milwaukee, 2000.)

could only delay the onset of expansion, whereas with high amount of fly ash (45%), concrete was immune to ASR (Figure 12.14).

A study by Shao et al.[116] on the partial replacement of cement by finely ground postconsumer glass, obtained from recycled fluorescent lamps, reported that the postconsumer glass finer than 38 μm could be used for the replacement of up to 30% of cement in the concrete. They concluded that the glass, ground finer than 38 μm, exhibited a pozzolanic behavior. The strength activity indices of concrete with 30% cement replacement by finer than 38 μm glass were 108%, exceeding the minimum 75% as recommended by ASTM C 618.[117] They observed expansion in mortar bars with the finely ground glass of just half of that in the concrete mixture without glass. They concluded that the lime activity index, strength development, and reduction in expansion were indicative of the pozzolanic activity of postconsumer glass. Their study further revealed higher strength development in the postconsumer glass concrete compared to the use of ASTM Class F fly ash but lower than concrete

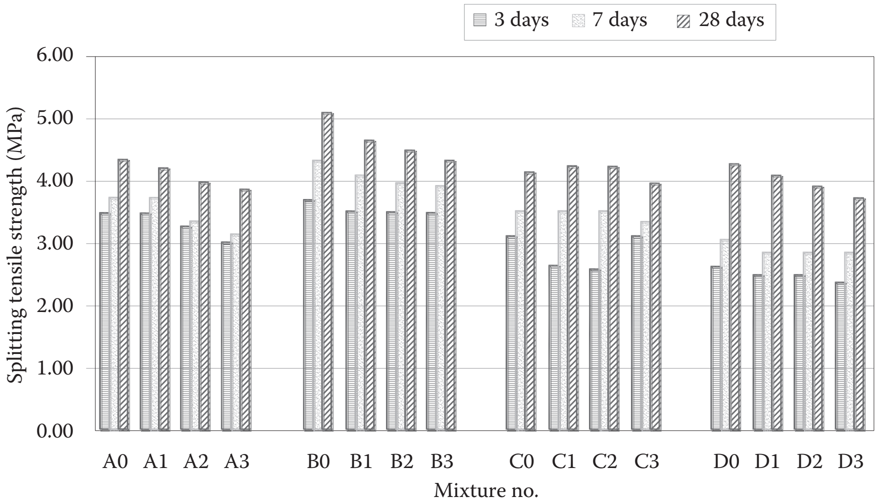

FIGURE 12.13 Tensile strength development of concrete mixtures for replacement of sand with crushed glass. A0, A1, A2, and A3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume), respectively. B0, B1, B2, and B3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume) and 15% cement replaced with Class C fly ash by mass on replacement level of 1:1.25, respectively. C0, C1, C2, and C3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume) and 30% cement replaced with Class C fly ash by mass on replacement level of 1:1.25, respectively. D0, D1, D2, and D3 are concrete mixtures with 0%, 15%, 30%, and 45% sand replaced with crushed glass (by volume) and 45% cement replaced with Class C fly ash by mass on replacement level of 1:1.25, respectively. (From Naik, T.R., and Wu, Z., Crushed post-consumer glass as a partial replacement of sand in concrete, *Report No. CBU-2000-17*, Center for By-Products Utilization, University of Wisconsin-Milwaukee, 2000.)

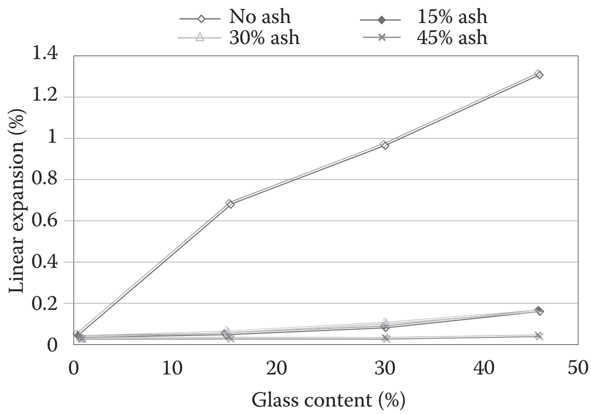

FIGURE 12.14 28-day linear expansion of concrete mixtures versus crushed glass content. (From Naik, T.R., and Wu, Z., Crushed post-consumer glass as a partial replacement of sand in concrete, *Report No. CBU-2000-17*, Center for By-Products Utilization, University of Wisconsin-Milwaukee, 2000.)

TABLE 12.9
Chemical Compositions of Soda Lime Glass, Class F Fly Ash, and Silica Fume (% Weight)

Chemical Compositions	Soda Lime Glass	Class F Fly Ash	Silica Fume
SiO_2	72.8	40.71	96.5
Al_2O_3	1.4	17.93	0.5
Fe_2O_3	–	29.86	2.0
$SiO_2 + Al_2O_3 + Fe_2O_3$	74.2	88.50	99.0
CaO	4.9	2.80	0.80
MgO	3.4	1.09	0.90
SO_3	–	1.27	0.20
K_2O	0.3	1.56	2.0
Na_2O	16.3	0.73	0.40
P_2O_5	–	0.17	–
TiO_2	–	0.85	–
B_2O_3	1.0	–	–
Color	White	Gray	Dark

Source: Shao, Y. et al., *Cement and Concrete Research*, Vol. 30, No. 1, pp. 91–100, 2000.

containing silica fume. The chemical compositions of soda lime glass used in the study along with fly ash and silica fumes are given in Table 12.9.

Similar results were observed by Dyer and Dhir[118] in their study on the use of glass cullet as a cement component. In their study, they used glass powder that passed through a 600-μm sieve to ensure that the large particles did not remain. White, green, and amber glass cullets were used. Based on the results, they suggested that the pozzolanicity of finely ground glass cullet (GGC) could be exploited by using it as a cement component in the concrete. They further reported a reduction in the expansion due to the ASR of mortars containing GGC, which was attributed to the rapid pozzolanic rate of reaction of the finely ground GGC than the slower ASR. Ahmad[119] used fine glass powder of less than 10 μm size obtained from postconsumer glass as a pozzolanic material to replace a part of cement and to suppress the alkali reactivity of coarser glass particles as well as that of natural reactive aggregates in concrete. He demonstrated that up to 30% replacement of cement by fine glass powder is possible with satisfactory strength development. He further reported that the use of glass powder in concrete would prevent expansive ASR in the presence-susceptible aggregate.

12.11 RECYCLING OF DISCARDED CEMENT CONCRETE ROAD SLABS FOR SUSTAINABLE CONCRETE

Recycling concrete for aggregates is one of the leading approaches toward sustainability in the construction sector as aggregates account for 70%–80% of concrete. The recycling of discarded concrete pavement slabs for the manufacturing of good quality aggregate is more advantageous over the C&D debris. Table 12.10[120] presents

TABLE 12.10
C&D Waste Generated and Recycled

Country	Waste Generated (Metric Tonne)	Percentage of Recycling	Percentage of Landfill
United States	180	56	44
Germany	59	17	83
United Kingdom	30	45	55
France	24	15	85
Italy	20	9	91
India	12	NA	NA

Source: Krishna, V. and Kumar, R., *International Journal of Research in Engineering and Technology (IJRET)*, Vol. 2, No. 2, pp. 59–65, 2013.
Note: Unfortunately, recycling data are unavailable in India.

TABLE 12.11
Percentage of Concrete and Major Components in C&D Waste

Concrete	52
Wood	20
Glass	10
Plastic	4
Metal	3
Other	7

Source: Nisbet, M., Venta, G., and Foo, S., Construction and Demolition Waste in Canada. Prepared by SENES Consultants for Environment Canada, Ottawa, 1993.

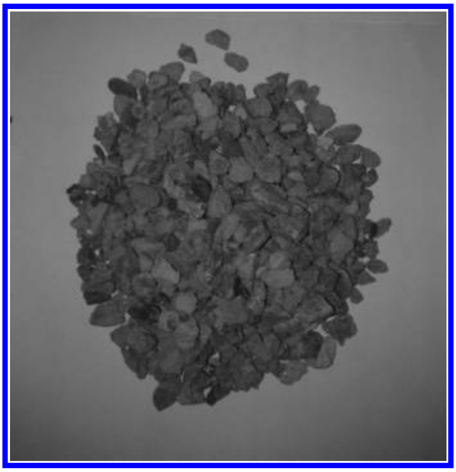

FIGURE 12.15 Recycled aggregate from C&D waste.

the C&D generated and recycled for a few countries, whereas Table 12.11[121] shows the percentage of concrete and other components of it.

Figure 12.15 shows a picture of recycled aggregate obtained from a C&D recycling plant in India.

12.11.1 Advantages of Recycling of Cement Concrete Roads over C&D Wastes

Recycling aggregates from discarded cement concrete roads offers several benefits of saving time, money, and GHG emissions in comparison with recycling C&D wastes for aggregate. Recycling aggregates from C&D wastes (from old buildings) consumes more time as concrete road can be considered as a homogeneous member (a building can be considered heterogeneous as it has beams, columns, slabs, and other different components). Thus, recycling the aggregates from plain cement concrete road slabs is much easier than the former (easier if free from reinforcements). Moreover, aggregates from demolished concrete pavement slabs are free from several impurities. Table 12.12 shows contaminants found in C&D wastes from buildings.[121]

The most important factor in favor of recycling of plain cement concrete pavement slab is that it is free from the above-mentioned impurities. Thus, washing and cleaning are not required. According to Technology Information Forecasting Assessment Council (India), demolition of Pucca and Semi-Pucca buildings, on an average, generates 500 and 300 kg/m^2 of concrete waste, respectively, including contamination, whereas a cracked or demolished pavement slab can give an aggregate up to 11,500 kg free from any contamination.[122] The quantity of recycled aggregate obtained from demolished concrete pavement is comparatively much more. This minimizes the environmental impact by reducing the carbon footprint, embodied energy, and emissions and enhances social good by reducing the need for landfills and the extraction of nonrenewable aggregates, which are social factors toward sustainability. Table 12.13 shows the advantages of recycling of cement concrete roads over C&D wastes.

When the recycled concrete is to be used as an aggregate in Portland cement concrete, usually 80% of the slab is removed.[123] Further economic benefits can be obtained by recycling work done on the site and by using aggregate on the spot.

TABLE 12.12
Contaminants in C&D Debris

Contaminants	Volume % of Aggregate
Lime plaster	7
Soil	5
Wood	4
Gypsum	3
Asphalt	2
Paint	0.2

Source: ftp://ftp.tech-env.com/pub/RETROFIT/awma%20paper_wm1b.pdf.

TABLE 12.13
Advantages of Recycling of Cement Concrete Roads over C&D Wastes

Cement Concrete Roads	C&D Debris
Consume less time.	Consumes more time.
Quantity of aggregate is quite large.	Quantity of aggregate is less.
Contain 0% impurities.	Contains more amount of impurities.
Grade of concrete is uniform.	Grade of concrete varies.
Aggregate can be used on site.	Aggregate may or may not be used on site.
Operation is less costly.	Operation is quite expensive.

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13 Sustainability of Steel Reinforcement

Subramanian Narayanan and Mike Mota

CONTENTS

13.1 INTRODUCTION

Plain concrete has two major deficiencies: low tensile strength and low strain at fracture. The tensile strength of concrete is very low because plain concrete normally contains numerous microcracks. It is the rapid propagation of these microcracks under applied stress that is responsible for the low tensile strength of the material. These deficiencies have led to considerable research aimed at developing new approaches to modifying the brittle properties of concrete (Subramanian 2013). The most common approach is to add reinforcement to the tensile zone of concrete. Concrete reinforcement may be in the form of reinforcing bars (rebars), mesh, strand,

and even different types of fibers (when fibers are included, the product is referred to as *fiber-reinforced concrete [RC]*). Reinforcement plays an important role in structural concrete for a number of reasons: resisting tensile stresses (due to direct tension, bending, shear, etc.), crack bridging, ductility, and confinement. We will confine our attention only on rebar, prestressing steel (including pre-tensioning and post-tensioning), and welded wire reinforcement.

Reinforcements in the form of steel rods are often used to resist the tensile stresses developed in concrete due to the applied forces. Steel is more ideal for reinforcement because it has similar thermal expansion coefficient, binds well to concrete, and is strong and relatively cost effective. The amount of steel tension reinforcement used in RC flexural members may range from 0.12% to about 1.0% (using high-strength deformed bars). An area of compression reinforcement at least equal to one-half of tension reinforcement should be provided in flexural members in order to ensure adequate ductility at potential plastic hinge zones and to ensure that minimum of tension reinforcement is present for moment reversal (Subramanian 2010b). In compression members, the amount of steel reinforcement may be in the range of 0.8%–4%.

Different types and grades of steel reinforcements are available. The main problem of steel reinforcement is its corrosion when exposed to severe atmosphere. Various corrosion mitigation strategies have been developed including using corrosion-resistant coatings and alloys. *Steel is almost 100% recyclable and more sustainable than other materials.* Life-cycle inventory (LCI)/life-cycle assessment (LCA) and the US Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED®) could be used to measure the sustainability. The methods and strategies adopted for the sustainability of buildings are also bridges and other infrastructure systems.

13.2 BUILDING GREEN WITH RC

As discussed in Chapters 3, 5, and 11, RC can be made green by adopting various strategies like replacing Portland cement with industrial by-products such as fly ash and steel slag, reducing or capturing CO_2 emissions during the production stage of cement, using efficient mixes with less cement content, enhancing the design service life of structures, using geopolymer concrete, adopting green cements, etc. But the sustainability of reinforcements was not discussed because steel, which is invariably used as the material of choice for reinforcement, is the most recycled material on earth, more than all other materials combined. However, it is prone to corrosion and has to be protected to give a longer life.

13.2.1 Brief History of Steel Reinforcement

Even though concrete is strong in compression, it is very weak in tension. Hence, some kind of reinforcement is necessary to make it strong in tension as well. The small rowboats built by Jean-Louis Lambot in the early 1850s are cited as the first successful use of reinforcements in concrete. Joseph Monier of France, who is considered as the first builder of RC, built RC reservoirs in 1872. In 1861, Monier published a small book, *Das System Monier*, and presented applications of RC. During 1871–75, William E. Ward built the first landmark building in RC in Port Chester, NY, USA. In 1892, François Hennebique of France patented a system of steel-reinforced beams, slabs, and columns, which was used in the construction of various structures built in England between 1897 and 1919. In Hennebique's system, steel reinforcement was placed correctly in the tension zone of the concrete; this was backed by a theoretical understanding of the tensile and compressive forces, which was developed by Cottançin in France in 1892 (Reed et al. 2008).

Ernest L. Ransome patented a reinforcing system using twisted rods in 1884; he also built the first RC-framed building in Pennsylvania, USA in 1903. In 1889, the first concrete-reinforced bridge was built. In 1902, the rotary kiln was improved by Thomas Edison. The Ingalls building, the first concrete skyscraper, using the Ransome system, was built in 1904, which is still in use.

By the 1900s, concrete was generally used in conjunction with some form of reinforcement, and steel began to replace wrought iron as the predominant tensile material. A significant advance in the development of RC was the prestressing of the steel reinforcement, which was developed by Eugène Freyssinet, in the 1920s, but the technique was not widely used until the 1940s. (Walnut Lane Memorial Bridge in Philadelphia, built in 1951, was the first prestressed concrete bridge in the United States. The first prestressed concrete bridge in India was built in 1954 over the Palar River in Tamilnadu.) Victoria skyscraper in Montreal, constructed in 1964, with a height of 190 m and utilizing 41-MPa concrete in the columns, paved the way for high-strength concretes (Shaeffer 1992).

In 1908, Prof. Mörsch and Bach of the University of Stuttgart conducted a large number of tests to study the behavior of RC elements. Prof. Mörsch's work can be considered as the starting point of the modern theory of RC design. The straight line (elastic) theory of Coignet and Tedesco (usually called the *working stress method*) developed during the 1900s was first used for the design of RC elements universally because of its simplicity. The *ultimate strength design* was adopted as an alternative to the working stress method only in 1956–1957. Most of the modern codes of practices use the *limit states method*, which was first introduced in the British Code CP 110 in 1972 (now BS 8110).

13.3 TYPES OF REINFORCING STEEL

As mentioned earlier, steel reinforcements are provided in roller-compacted concrete (RCC) to resist tensile stresses and add stiffness to concrete elements. Steel rebars make up 44% of steel used in buildings (Worldsteel Association 2012). The quality of steel used in RCC work is as important as that of cement. Steel bars used in concrete should be clean and free from loose mill scales, dust, loose rust, and any oily material, which will reduce bond. Sand blasting or similar treatment may be done to get clean reinforcement. Steel reinforcement (often called *rebars* in the United States) is available in different grades and specifications depending on its yield strength, ultimate tensile strength, chemical composition, and percentage of elongation.

13.3.1 Different Grades of Steel Rebars

In the United States, the grade designation is based on the minimum yield strength of the bar in ksi (1000 psi); thus, for example, grade 60 rebar has a minimum yield strength of 60 ksi (415 N/mm^2 in SI units). Usually, rebars are manufactured in grades of 40 (equivalent SI grade Fe 275), 60 (Fe 415), and 75 (Fe 520). Other grades that may be available are 50 (Fe 345), 80 (Fe 550), and 100 (Fe 690).

13.3.1.1 American Society for Testing and Materials Grades for Rebars, Fibers, and Headed Rebars

As per Clause 3.5.3 of ACI 318-11, the American Society for Testing and Materials (ASTM) specifications for rebars are as given below:

- ASTM A615/A615M-09: Standard Specification for Deformed and Plain Carbon Steel Bars for Concrete Reinforcement
- ASTM A706/A706M-09: Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement
- ASTM A955/A955M-10: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement
- ASTM A996/A996M-09: Standard Specification for Rail-Steel and Axle-Steel Deformed Bars for Concrete Reinforcement (Type R)
- ASTM A1035/A1035M-09: Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement (used for transverse reinforcement or spiral reinforcement)
- ASTM A184/A184M-06: Standard Specification for Welded Deformed Steel Bar Mats for Concrete Reinforcement (Reinforcing bars used in bar mats should conform to ASTM A615 or ASTM A706)
- ASTM A767/A767M-09: Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement
- ASTM A775/A775M-07: Standard Specification for Epoxy-Coated Steel Reinforcing Bars
- ASTM A884/A884M-06: Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Reinforcement
- ASTM A934/A934M-07: Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars
- ASTM A1022/A1022M-07: Standard Specification for Deformed and Plain Stainless Steel Wire and Welded Wire for Concrete Reinforcement
- ASTM A1055/A1055M-10: Standard Specification for Zinc and Epoxy Dual-Coated Steel Reinforcing Bars
- ASTM A1060/A1060M-10: Standard Specification for Zinc-Coated (Galvanized) Steel Welded Wire Reinforcement, Plain and Deformed, for Concrete
- ASTM A1064/A1064M-10: Standard Specification for Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete

Steel for prestressing should conform to one of the following specifications:

a. Wire: A421/A421M-10 (Standard Specification for Uncoated Stress Relieved Steel Wire for Prestressed Concrete)
b. Low-relaxation wire: ASTM A421M-10, including Supplementary Requirement S1 “Low-Relaxation Wire and Relaxation Testing”

c. Strand: A416/A416M-10 (Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete)
d. High-strength bar: A722/A722M-07 (Standard Specification for Uncoated High-Strength Steel Bars for Prestressing Concrete)

Other ASTM specifications pertaining to fibers, studs, and headed rebars used in RC are given below:

- A307-10 Standard Specification for Carbon Steel Bolts and Studs, 60,000 psi Tensile Strength
- A820/A820M-06 Standard Specification for Steel Fibers for Fiber-Reinforced Concrete
- A970/A970M-09 Standard Specification for Headed Steel Bars for Concrete Reinforcement including Annex A1 Requirements for Class HA Head Dimensions
- A1044/A1044M-05 Standard Specification for Steel (2010) Stud Assemblies for Shear Reinforcement of Concrete

The rebars manufactured under ASTM specifications are marked with designations as below (see also Figure 13.1):

- "S" Carbon steel–A615
- "I" Rail steel–A996
- "R" Rail steel–A996
- "A" Axle–A996
- "W" Low-alloy steel–A706

Thus, each individual reinforcing bar is manufactured with a series of individual markings (see Figure 13.1):

- The top letter or symbol identifies the producing mill.
- The next marking is the bar size (imperial bar sizes give the diameter in units of ⅛ in.; hence, the marking of #8 on a bar denotes 8⁄8-in. or 1-in. diameter rebar)
- The third marking symbol denotes the material used in the rebar as discussed above; thus, the letter "S" denotes carbon-steel (ASTM A615).
- The fourth marking shows the grade of steel (the marking 4 [60] or 5[75] denotes 420 or 520 N/mm^2). The grade may also be shown by the addition of one line (420 N/mm^2) or two lines (520 N/mm^2) that must be at least five deformations long.

13.3.2 Steel Reinforcement Used in RC

As per Clause 3.5.1 of ACI 318-11, only deformed rebars should be used as main reinforcement; plain rebars are permitted for spirals or prestressing steel only. In addition, this code permits the use of reinforcement consisting of headed shear

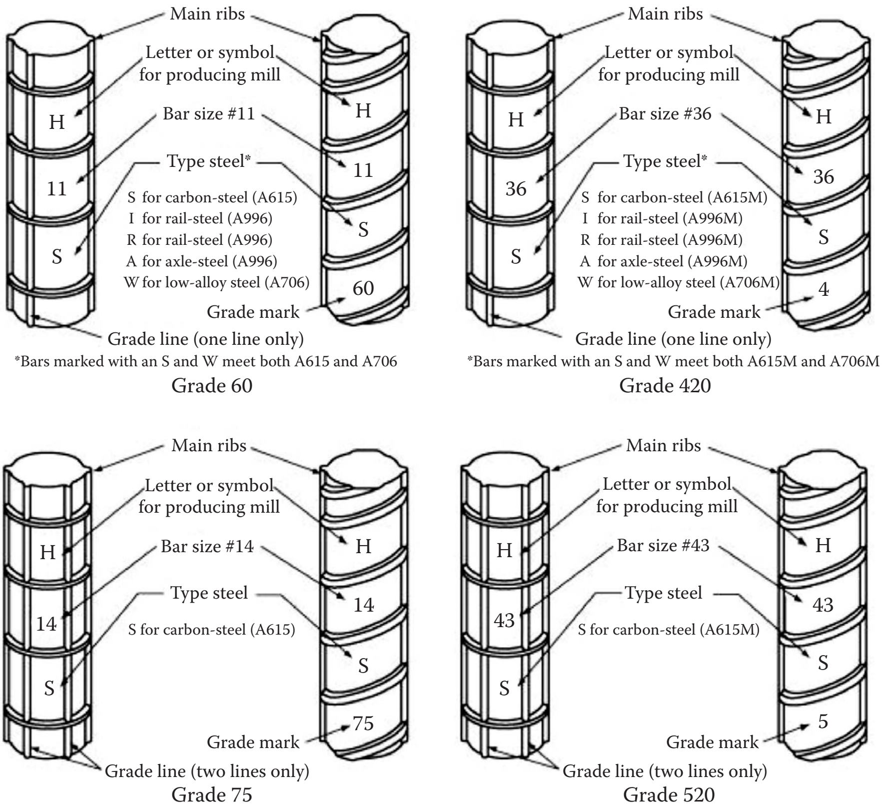


FIGURE 13.1 Typical ASTM bar marking sequence. (From http://www.crsi.org/index.cfm/steel/identification.)

studs, structural steel, steel pipe, or steel tubing also in certain cases. Discontinuous deformed steel fibers should be used only for resisting shear under certain conditions specified in the code. Welded, deformed wire reinforcement mats should be made of wire conforming to ASTM A1064M, which specifies minimum yield strength of 485 MPa. ACI 318 has assigned a yield strength value of 420 MPa but makes provision for the use of higher yield strengths provided the stress corresponds to a strain of 0.35%.

As per Clause 5.6 of IS 456, steel reinforcement used in concrete may be of the following types (see Table 1.1 of SP 34 [S&T]: 1987 for the physical and mechanical properties of these different types of bars):

1. Mild steel and medium tensile steel bars conforming to IS 432 (Part 1): 1982
2. High-strength deformed steel bars (HYSD bars) conforming to IS 1786: 2008

3. Hard-drawn steel wire fabric conforming to IS 1566:1982
4. Structural steel conforming to Grade A of IS 2062:2006

Note that different types of rebars, such as plain and deformed bars of various grades, say, grade Fe 415 and Fe 500, should not be used side by side, as this may lead to confusion and error at site. Mild steel bars, which are produced by hot rolling, are not generally used in RC as they have a smooth surface, and hence their bond strength is less compared to deformed bars (when they are used, they should be hooked at their ends). They are only used as ties in columns or stirrups in beams. Mild steel bars have characteristic yield strength ranging from 240 N/mm^2 (grade I) to 350 N/mm^2 (medium tensile steel) and percentage elongation of 20%–23% over a gauge length of $5.65\sqrt{\text{area}}$.

- *Hot-rolled HYSD bars*: These bars were introduced in India during 1967 and completely replaced mild steel bars except in a few situations where acute bending was required in bars greater than 30 mm in diameter. They were produced initially by cold twisting (cold-twisted deformed bars [CTD bars]) and later by heat treatment (thermo-mechanically treated reinforcement bars [TMT bars]) and micro-alloying. They were introduced in India by Tata Steel as Tistrong bars and later as Tiscon/Torsteel bars. *CTD bars* or *Torsteel bars* are first made by hot rolling the bars from high-strength mild steel, with two or three parallel straight ribs and other indentations on it. After cooling, these bars are cold twisted by a separate operation, so that the steel is strained beyond the elastic limit and then released. As the increase in strength is due to cold working, this steel should not normally be welded (Subramanian 2013). In CTD bars, the projections will form a helix around the bars—if they are overtwisted, the pitch of the helixes will be too close. Cold twisting introduces residual stresses in steel, and hence these bars corrode much faster than other bars—hence, they are not recommended in many advanced countries.
- *TMT bars*: TMT bars are a class of hot-rolled HYSD bars, which are rapidly cooled to about 450°C by a controlled quenching process using water when they are leaving the last stand of the rolling mill at a temperature of about 950°C (Subramanian 2013). This sudden partial quenching, along with the final cooling, transforms the surface layer of the bars from austenite to tempered martensite, with a semi-tempered middle ring of martensite and bainite and a fine-grained ferrite–pearlite core. These bars therefore exhibit a variation in microstructure in their cross section, having strong, tough, and tempered martensite in the surface layer and a refined, tough, and ductile ferrite and pearlite core (see Figure 13.2). In TMT bars, the carbon content can be restricted to 0.2% to attain weldability, and at the same time, no strength is lost on this account. TMT bars can be welded as per IS 9417 using ordinary electrodes, and no extra precautions are required. Strength, weldability, and ductility are the main advantages of TMT bars; in addition, they are also economical. TMT bars produced by Steel Authority

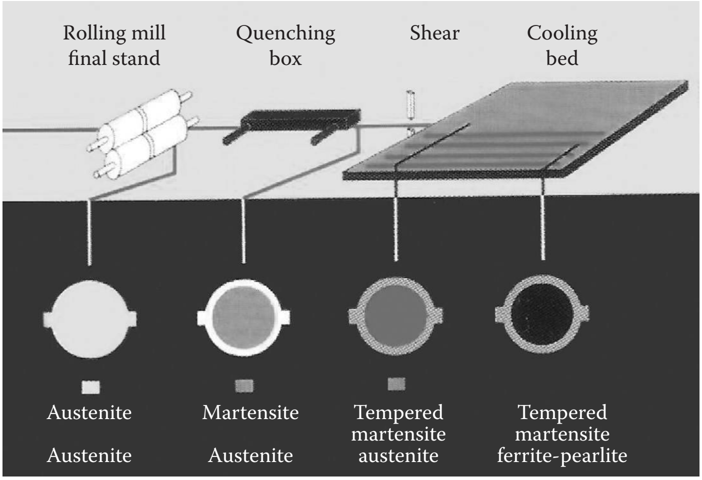


FIGURE 13.2 Manufacturing process of TMT bars. (From Subramanian, N., *Design of Reinforced Concrete Structures*, Oxford University Press, New Delhi, 2013.)

of India Ltd. (SAIL) or Tata are known as SAIL-TMT or Tiscon-TMT. Bars produced by Rashtriya Ispat Nigam Ltd. (RINL, also known as Vizag Steel) are called rebars. As it is visually difficult to distinguish TMT bars from mild steel-deformed bars, the following procedure is suggested in IS 1786: A small piece (about 12 mm long) can be cut, and the transverse face lightly ground flat on progressively finer emery papers up to "0" size. The sample can be macro-etched with nital (5% nitric acid in alcohol) at ambient temperature for a few seconds to reveal a darker annular region corresponding to martensite/bainite microstructure and a lighter core region.

By micro-alloying with elements like copper, phosphorus, and chromium, *TMT corrosion-resistant steel bars* (TMT-CRS bars) are produced, which have better corrosion resistance than ordinary TMT bars (Subramanian 2013). It is better to adopt precautions against corrosion even while using such bars, as they are not 100% corrosion proof. Though IS 1786 specifies four grades: Fe 415, Fe 500, Fe 550, and Fe 600 and additional three grades with a suffix D, denoting that they are ductile, for these HYSD bars, the availability of Fe 550, Fe 600, Fe 415D, Fe 500D, and Fe 550D grades are limited (the numbers after Fe denoting the 0.2% proof stress/yield stress, in N/mm^2).

The most important characteristic of the reinforcing bar is its stress–strain curve, and the important properties are its characteristic yield strength or 0.2% proof stress as the case may be (see Figure 13.3); as per Clause 5.6.3 of IS 456, the modulus of elasticity E_s for these steels may be taken as 200 kN/mm^2. The chemical composition of various grades of steel is given in IS 1786:2008.

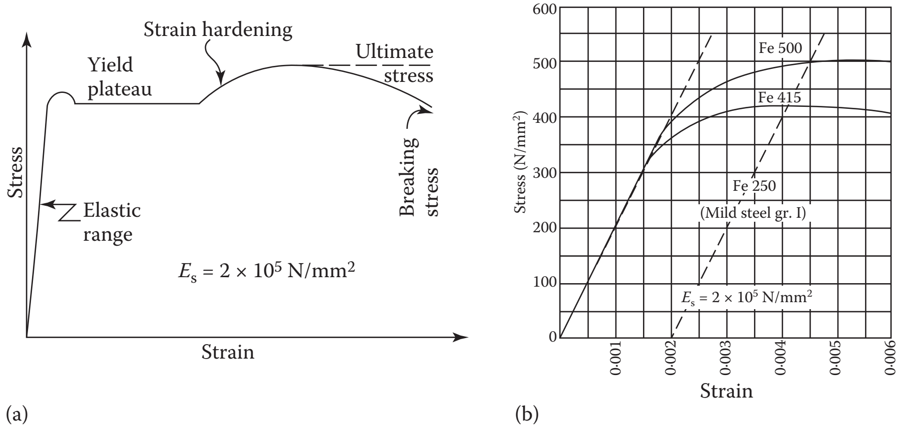


FIGURE 13.3 Stress–strain curve for (a) mild steel, (b) HYSD bars.

Clause 5.3 of IS 13920 stipulates that steel reinforcements of grade Fe 415 or less only should be used in structures situated in earthquake zones. However, TMT bars of grades Fe 500 and Fe 550, having elongation more than 14.5%, are also allowed. For providing sufficient bond between the bars and the concrete, the area, height, and pitch of ribs should satisfy Clause 5 of IS 1786 (see Figure 13.4). The nominal size of available bars as per IS 1786 are as follows: 4, 5, 6, 8, 10, 12, 16, 20, 25, 28, 32, 36, and 40 mm. A density of 7850 kg/m³ may be taken for calculating the nominal mass.

- *Welded wire fabrics (WWF)*: WWF consist of hard-drawn steel wire mesh made from medium tensile steel, drawn out from higher-diameter steel bars. As they undergo "cold working," their strength is higher than that of mild steel. WWF consist of longitudinal and transverse wires (at right angles to one another) joined by resistant spot welding using machines. They are

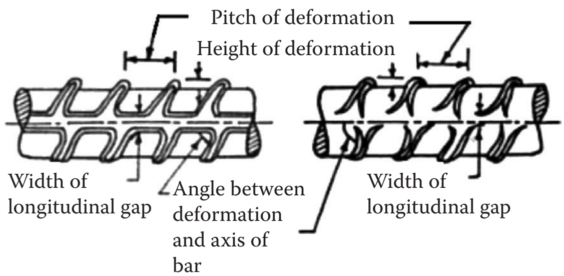


FIGURE 13.4 Deformation on bars.

available in different widths and rolls and as square or oblong meshes (see Table C-1 of SP 34 [S&T]: 1987 and SP 1566:1982). Their use in India is limited to small-size slabs.
- *High-strength rebars*: In addition to these rebars, *Zbar*, a pretreated high-strength rebar with both galvanizing and epoxy coating, has recently been introduced in United States. High-strength *micro-composite multi-structural formable (MMFX) steel bars*, conforming to ASTM A1035, with yield strength of 827 MPa and having low carbon and 8%–10% chromium have also been introduced in the United States recently, which are also corrosion resistant, similar to TMT-CRS bars (http://www.mmfx.com).

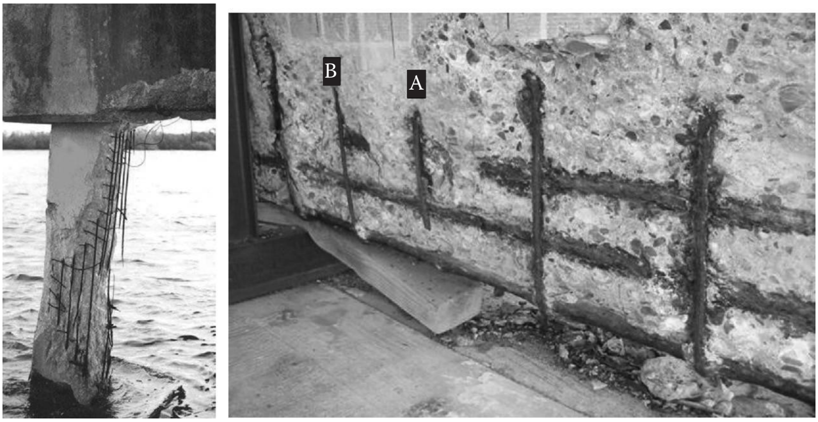
High-grade reinforcing steel, wire and welded wire reinforcing, and prestressed structures can all contribute to reducing the amount of reinforcement and/or concrete required to achieve the same or higher strength and performance. Any reduction in the total mass of materials reduces the impact of their manufacture and transportation. Reduced mass in the building has a ripple effect by reducing the material needed for the foundation to support the structure. In the case of post-tensioned slabs, the floor-to-floor heights can be reduced, lowering the overall building height, the materials needed to vertically service all the floors (e.g., piping, conduit), and the energy required to provide vertical distribution (fans and pumps) as well as to condition the reduced space in the thermal envelope.

Prestressed reinforcement is typically designed at a level of force so that the structural members are uncracked at service levels. When combined with low-permeability, high-quality concrete, the reinforcing steel is protected from corrosion. In post-tensioned systems, either grout or a grease-like coating provides an additional layer of corrosion protection for the strand.

High-strength (Grade 80) and very high-strength (Grades 100 and 120) steel reinforcing bars and welded wire reinforcement are ductile materials with high yield and ultimate strengths. In blast-resistant structures, concrete can absorb some of the blast, whereas the reinforcing steel retains the core concrete and minimizes the flying debris. The concrete wall system can serve to stop flying debris from other parts of the building. The elongations of the reinforcement steel before breaking also provide energy absorption to reduce blast effects.

13.4 CORROSION OF STEEL REINFORCEMENT

It has been recognized that much of the concrete in the infrastructure in the United States, India, and elsewhere is deteriorating faster than expected; the main cause of this deterioration is the corrosion of reinforcing steel coming from the ingress of chloride and other ions from road salts, marine environments, and ground soils. Corrosion costs US industry and government agencies an estimated $276 billion/year (approximately 3.1% of the gross domestic product [GDP]), according to the study by C & C Technologies for the Federal Highway Administration (Koch et al. 2002). A corroded RC element in a typical marine application and a bridge structure are shown in Figure 13.5. With more than 7000 km of coastline, India has significant issues with salt water corrosion of its infrastructure. Air pollution and the resulting



(a) (b)

FIGURE 13.5 (a) Heavily corroded reinforcements in a typical marine structure. (From http://www.dnvusa.com/Binaries/highway_tcm153-378806.pdf.) (b) Chloride-induced corrosion damage to a beam of the Brush Creek Bridge, USA. (From http://cce.engr.oregonstate.edu/structural/corrosion.html.)

carbonation of concrete also contribute to corrosion. Humid climate in much of the country aids metallic corrosion. The cost of corrosion in India has been estimated to be 3% of its GDP—$30 billion.

13.4.1 Effect of Corrosion on Bridges

Corrosion of steel rebars is considered as the main cause of deterioration of numerous RCC structures throughout the world. In fact, the alkaline environment of concrete (pH of 12 to 13) provides a thin, passive oxide film over the surface of steel rebars and reduces the corrosion rate considerably. For steel bars surrounded by sound concrete, the passive corrosion rate is typically 0.1 μm/year. Without the passive film, the steel would corrode at rates at least 1000 times higher (ACI 222 2001).

The destruction of the passive layer occurs when the alkalinity of the concrete is reduced or when the chloride concentration in concrete is increased to a certain level. In many cases, exposure of RC to chloride ions is the primary cause of premature corrosion of steel reinforcement. Although chlorides are directly responsible for the initiation of corrosion, they appear to play only an indirect role in the rate of corrosion after initiation. The primary factors controlling the corrosion rate are the availability of oxygen, the electrical resistivity and relative humidity of the concrete, the pH, and the prevailing temperature.

Carbonation is another cause of corrosion. Carbonation-induced corrosion often occurs in building facades that are exposed to rainfall, are shaded from sunlight, and have low concrete cover over the reinforcing steel. Carbonation occurs when carbon dioxide from the air penetrates the concrete and reacts with hydroxides, such as calcium hydroxide, to form carbonates. (It has to be noted that the concentration of CO_2 in the atmosphere has increased from 310 ppm in 1950 to 400 ppm in 2014.) In the reaction with calcium hydroxide, calcium carbonate is formed. This reaction reduces the pH of the pore solution to as low as 8.5, destroying the passive film on steel rebars. Note that carbonation is generally a slow process. In high-quality concrete, carbonation is estimated to proceed at a rate up to 1.0 mm/year (http://www.cement.org). The highest rates of carbonation occur when the relative humidity is maintained between 50% and 75% (http://www.cement.org). The amount of carbonation is significantly increased in concrete with a high water/cement ratio, low cement content, short curing period, low strength, and highly permeable paste (http://www.cement.org). Corrosion can also occur when two different metals are in contact within concrete. For example, *dissimilar metal corrosion* can occur in balconies where embedded aluminum railings are in contact with the reinforcing steel.

Conventional concrete contains pores or microcracks. Detrimental substances or water can penetrate through these cracks or pores, leading to corrosion of steel bars. When corrosion takes place, the resulting rust occupies three times the original volume of steel from which it is formed. This drastic expansion creates tensile stresses in the concrete, which can eventually cause cracking, delamination, and spalling of cover concrete (see Figure 13.1). The presence of corrosion also reduces the effective cross-sectional area of the steel reinforcement and may lead to the failure of a concrete element and subsequently the whole structure.

13.4.2 Mitigation of Corrosion

There are a wide variety of measures to reduce the occurrence of corrosion, each with its own special advantages and economics. They include the following:

- Decreasing the w/c or *w/cm ratio* of concrete and using pozzolans and slag to make the concrete less permeable; pozzolans and slag also increase the resistivity of concrete thus reducing the corrosion rate even after it is initiated.
- Providing dense concrete cover, thus protecting the embedded steel rebars from corrosive materials; the thickness of required cover is to be fixed based on the environmental condition that the structure experiences

(dense concrete cover may be obtained by using *controlled permeability formwork*).

- Including the use of corrosion-inhibiting admixtures.
- Providing protective coating to reinforcement.
- Using sealers and membranes on the concrete surface.
- Using corrosion-resistant alloys.
- Using cathotic and anodic protection. Note that sealers and membranes, if used, have to be reapplied periodically (Kerkhoff 2007).

As stated above, one of the corrosion mitigation methods is to use the following reinforcements (Subramanian 2013):

1. *Fusion-bonded, epoxy-coated reinforcing rebars*: Typical coating thickness used on these rebars is about 130 to 300 μm. Damaged coating on the rebars, resulting from handling and fabrication and the cut ends, must be properly repaired with patching material prior to placing them in the structure. These rebars have been used in RC bridges from the 1970s, and their performance is found to be satisfactory (Smith and Virmani 1996). The embodied energy of epoxy-coated rebars during manufacture is lower than that of other corrosion-resistant reinforcing steels. Epoxy-coated rebars cost less than other corrosion-protection systems. Table 13.1 shows the comparison of epoxy-coated rebars with other rebars.
2. *Galvanized reinforcing rebars*: The precautions mentioned for epoxy-coated rebars are applicable to these rebars also. The protective zinc layer in galvanized rebars does not break easily and results in better bond.
3. *Stainless steel rebars*: Stainless steel is an alloy of nickel and chromium. Two types of stainless steel rebars, i.e., SS304 and SS316, are used as per BS 6744:2001. Though the initial cost of these rebars is high, life cycle cost is lower, and they may provide 80–125 years of maintenance-free service. The Progresso Bridge in New Mexico, USA, was built in 1937–1941 using stainless rebars and has not required maintenance up to the present.

TABLE 13.1
Comparison of Epoxy-Coated Rebars with Other Reinforcing Types

Item	ASTM A615/ ASTM A706	ASTM A775/ A934	ASTM A1035	ASTM A767	ASTM A955
Percentage recycled	>97	>97	>75	>97	>75
Embodied energy	Low	Low	High	Moderate	High
Availability	Nationwide	Nationwide	Single source	Multiple sources	Few sources
Durability	Low	High	Moderate	Moderate	Very high
Cost	Low	Low	Moderate	Moderate	Very high

4. *Fiber-reinforced polymer (FRP) rebars*: These are aramid fiber- (AFRP) or carbon fiber- (CFRP) or glass fiber-reinforced polymer (GFRP) rebars. They are nonmetallic and hence noncorrosive. Although their ultimate tensile strength is about 1500 MPa, their stress–strain curve is linear up to failure, they have one-fourth weight, and they are more expensive than steel reinforcement. The modulus of elasticity of CFRP is about 65% of steel rebars, and bond strength is almost the same. As the Canadian Highway bridge design code, CSA–S6-06, has provisions for the use of GFRP rebars, a number of bridges in Canada are built using such rebars. More information can be found in GangaRao et al. (2007) and ACI 440R-07 (2007).
5. *Basalt rebars*: Basalt rebars are manufactured from continuous basalt filaments, epoxy, and polyester resins using a pultrusion process. It is a low-cost, high-strength, high-modulus, and corrosion-resistant alternative to steel reinforcement. More information on these rebars may be found in Subramanian (2010a).
6. Clause 5.6.2 of IS 456 suggests the use of coating to reinforcement, and Amendment 3 of this clause states that the reduction of design bond strength of coated bars should be considered in design, but it does not elaborate. See Sections 7.4.2 and 7.5.3 for the reduction of design bond strength based on ACI 318:11 provisions.

Based on their extensive experience of testing rebars, Viswanatha et al. (2004) caution about the availability of substandard rebars in India including rerolled bars and inadequately quenched or low-carbon content of TMT bars. Hence, it is important for the engineer to accept the rebars only after testing them in accordance with IS 1608:2005 and IS 1786:2008. Basu et al. (2004) also provide an overview of the important characteristics of rebars and a comparison of specifications of different countries.

Cathodic protection, which is an expensive option of corrosion control, is recommended wherever long-term protection is required on corrosion-damaged structures with a significant residual life or to new undamaged structures in aggressive chloride environments. Cathodic protection, powered with solar panels (where applicable), is a good method for protection against deicing salt-induced reinforcement corrosion in concrete structures and especially bridge decks (Mathur 2010).

13.5 APPLICATIONS OF RECYCLING FOR STEELS

Steel is one of the most sustainable building materials in the world. The metallurgical properties of steel allow it to be recycled continually with no degradation in performance and from one product to another. Recycling is very important for green economy as it conserves precious resources and prevents valuable materials going to landfills as waste.

13.5.1 Types of Metal Scrap

Even though there are a number of sources for steel scrap, they are generally classified into three main categories: home scrap, prompt scrap, and obsolete scrap.

Home scrap is the scrap metal that is produced from within the mill, foundries, and refineries and is available for recycling within a short period; it may include such scrap metal as turnings, cuttings, punchings, and borings. *Prompt scrap*, also known as industrial or new scrap metal, is generated by the metal working/fabrication industries and includes such scrap metal as turnings, cuttings, punchings, and borings. Home and prompt scrap together may be termed as *preconsumer scrap.* Prompt scrap is available for recycling within months of its original production. *Obsolete scrap* or *postconsumer scrap* is composed of worn-out metal or a metal product that is available for recycling at the end of their lives, such as discarded automobiles or ship hulks, railroad cars, aluminum beverage cans, steel beams/columns from torn-down buildings, and household appliances; it takes decades before this scrap is available for recycling.

Even while 2 out of every 3 tons of new steel is produced from old steel, it is still necessary to continue to use some quantities of virgin materials. This is true because many steel products remain in service as durable goods for decades at a time, and the demand for steel around the world continues to grow.

Beyond the steel scrap itself, the steel industry has long recycled its by-products: mill scale, steel-making slag, water, and processing liquids. Likewise, steel-making dusts and sludge are processed so that other metals, such as zinc, can be recovered and reused.

13.5.2 Recycling Processes

In general, metal recycling is a pyramid industry involving several small companies feeding scrap to a few large multinational companies. Steel recycling may involve some or all of the following processes:

- *Sorting*: Steel is separated from other recyclables like paper in a recycling facility with magnetic belts. It is not necessary to separate different kinds of steel.
- *Shredding*: Shredders incorporate rotating magnetic drums to extract iron and steel from the mixture of metals and other materials.
- *Media separation*: Further separation is achieved using electrical currents, high-pressure air flows, and liquid floating systems. Other processes may be necessary in cases such as steel cans, which have a protective layer of tin that must be removed and recycled separately.
- *Shearing*: Hydraulic machinery capable of exerting enormous pressure is used to cut thick, heavy steel recovered from railways and ships. Other cutting techniques, such as the use of gas and plasma arch, are sometimes employed.
- *Baling*: Iron and steel products are compacted into large blocks to facilitate handling and transportation.

13.5.3 Steel Production

Steel is produced usually by the blast furnace–basic oxygen furnace (BF-BOF) or by the electric arc furnace (EAF) (the open hearth furnace, which is very energy intensive and is declining due to the environmental and economical disadvantages, accounts for only 1% of global steel production). About 70% of steel is produced using the BF-BOF process and uses predominantly iron ore, coal, and recycled steel (as per http://www.aisc.org, the total recycled content in this process is 36.9%). The EAF process, which produces 29% of steel, uses mainly recycled steel and electricity (as per http://www.aisc.org, the total recycled content in this process is 89.89%).

The following improvements have been made in the steel-making process:

- More than 95% of the water used in the steel-making process is recycled and returned—often cleaner than when it was taken from the source.
- Since the early 1990s, the steel industry has reduced its energy use to produce a ton of steel by approximately one-third.

13.6 SUSTAINABILITY OF STEEL

As mentioned earlier, steel is one of the most sustainable building materials in the world. Steel's two key components are iron and recycled steel. It has to be noted that iron is one of earth's most abundant elements. Once steel is produced, it becomes a permanent resource, as it is 100% recyclable without loss of quality and has an endless life cycle. Steel has been recycled worldwide since 1900 (over 22 billion tonnes till now and 500 Mt annually). The combination of high strength, recyclability, availability, versatility, and affordability makes steel a very unique material. Each year, more steel is recycled than aluminum, paper, glass, and plastic combined. In 2009, 16 million tons of steel were generated in the United States, and 5 million tons were recovered. In the past 50 years, more than 50% of the steel produced in the United States has been recycled through the steel-making process.

According to the Bureau of International Recycling, almost 40% of the world's steel production is made from scrap, and steel recycling has the following benefits:

- Recycling 1 tonne of steel saves 1100 to 1400 kg of iron ore, 630 to 740 kg of coal, and 55 to 120 kg of limestone.
- CO_2 emissions are reduced by 58% through the use of ferrous scrap.
- Recycling 1 tonne of steel saves 642 kWh of energy, 1.8 bbl (287 L) of oil, 10.9 million Btu of energy, and 2.3 m^3 of landfill space.
- Recycling steel uses 75% less energy compared to creating steel from raw materials—enough to power 18 million homes.
- Steel recycling uses 74% less energy, 90% less virgin materials, and 40% less water; it also produces 76% fewer water pollutants, 86% fewer air pollutants, and 97% less mining waste.
- Whereas other products can only be recycled into a lower-quality product (downcycled), steel can be recycled over and over again and remade into new members without any loss of quality (multicycled). This makes it the first and only true cradle-to-cradle building framing material.

In regard to reinforcement, the recycled content is given as below (http://www.sustainableconcrete.org/?q=node/144):

- 97%: typical minimum recycled material content in reinforcing steel
- 75%: typical minimum recycled material content in specialty reinforcing steel, such as low-carbon chromium steel and stainless steel
- 92%–97%: typical recycled material content in wire and welded wire reinforcement
- 100%: recyclability of reinforcing steel after its useful life in a structure

Although reinforcing steel is currently recycled rather than reused, there is potential for reuse by assembling buildings from modular RC elements, such as standard floor slabs (Crowther 2002; Weiß 2007; Weiß and Reinhardt 2007, 2008; Allwood and Cullen 2012).

The research and development efforts undertaken by the steel industry has resulted in sustainable manufacturing process with (http://www.steelconstruction.info/Sustainability; Worldsteel Association 2012)

- Increased productivity by a factor of 24 since 1980 (reduced labor hours per ton from 12 to 0.5).
- Increased material strength by 40% since 1990 (250 to 415 MPa).
- Decreased energy use by 50% over the past 40 years.
- Decreased carbon footprint (per tonne) by 35% since 1990.
- Decreased energy intensity (per tonne) by 28% since 1990.
- Decreased greenhouse gas emissions (per tonne) by 60% over the past 40 years.
- Exceeded Kyoto Protocol improvement goals by 240%.
- Decreased material use. New lightweight steel is dramatically changing the market. In 1937, 83,000 tonnes of steel was needed to build the Golden Gate Bridge in San Francisco. Today, only half of that amount would be required.
- Almost 100% recovery rates. Current recovery rates from demolition sites in the United Kingdom are 99% for structural steelwork and 96% for all steel construction products—figures that far exceed those for any other construction material.

Today, steel has lower energy use and CO_2 emissions per ton than aluminum and magnesium among others.

To be sustainable, the design of steelwork should be such that it can be readily dismantled (bolted not welded connections) and of uniform length for reuse. Luckily, advances in computer software and engineering have made most modern steel structures extremely efficient, and designers are able to plan for minimal use of raw material to achieve the desired structural strength.

The embodied energy of steel is about 20 times higher than that of concrete (unreinforced) and about 20% that of aluminum. But embodied energy needs to relate to the weight or strength potential of the material and to the ability for subsequent material reuse. Both steel and aluminum have high energy costs in manufacture but relatively low recycled energy costs. It is no secret that you can do a lot more structurally with a tonne of steel than with a similar weight of concrete, and as many architects will testify, you can achieve a great deal more tectonic construction as well. (The Eiffel tower example is a perfect example of this.)

13.6.1 Life Cycle Assessment

Two of the most accepted and well-known methods for measuring sustainability are the combination of LCI/LCA and the USGBC's LEED. *Life-cycle cost analysis* (*LCCA*) is a standardized scientific method for the systematic analysis of all material cost and energy flows, as well as environmental impacts attributed to a product from raw material acquisition to end-of-life management. LCCA is considered a complete analysis (cradle to grave) of the true environmental impact of a product. If we run the steel manufacturing process through a full LCCA, we may get some interesting results. First, embodied energy is relatively insignificant as a proportion of the total energy used in a building. The amount of energy needed to produce a building (including manufacture, transport, and erection) is only a fraction of that consumed by the building during its lifetime involving heating, lighting, ventilation and other uses.

It is said that most of the steel needed for the future already exists in the form of buildings and other structures. New steel manufacture is needed merely to top up the supply that we already have, and already 50% of all new steel produced today consists of recycled material.

Another aspect to consider could be the weight of the building itself. The LCA also may highlight the transport energy costs, which are largely related to the weight of the material used. With steel being lighter than concrete (a typical steel building weighs about half that of a concrete one), it will require much less transport energy. In fact, weight is a useful, rough measure to assess the general environmental impact. Pollution, transportation, dust, nuisance, and noise are generally weight related—the heavier the building is, the greater the environmental impact will be. The stiffness allows steel to span greater distances and provides the designer greater freedom in the layout of columns than other materials. Steel's superior strength/weight ratio allows steel structures to bear higher loads using less material. (The use of high-strength concrete combined with high-strength steel reinforcement results in smaller size of columns, thus increasing the salable area of buildings.) Thus, less material is needed to make a quality structure, which also requires smaller foundations.

As steel building components can be cut to precise specifications and prefabricated at factory, on-site wastage is minimized. Any wastage that occurs in the factory can be directly recycled. Prefabricated steel components can be delivered to site and erected by a small number of skilled personnel. Moreover, there is no need for time-consuming and potentially hazardous shuttering and handling operations that are usually associated with materials like RC. As the prefabrication can speed up the construction process, the overall construction cost may be reduced. Shorter construction periods results in less disturbance to local community around the site. Moreover, steel is relatively clean and quiet to erect. Entire steel structures can be fully dismantled and reconstructed in a different location in a matter of days, without creating any dust and dirt, and with very little noise. Constructing a building from a demounted structure is one of the most sustainable ways of creating a "new" building, benefiting the local community and leaving behind no environmental legacy (http://www.steelconstruction.info/Sustainability).

13.6.2 LEED Credits Available for the Use of Epoxy-Coated Rebars

As stated in Chapter 3, the LEED green building rating system was developed by the USGBC and used by the Canadian Green Building Council. It is currently the most widely used rating system for environmentally sustainable design, construction, and operation of buildings and neighborhoods (see Section 3.5 for more details on green building rating systems).

The Materials & Resources Credit 4: Recycled Content category specifically focuses on increasing the use of building products with high recycled content, thus reducing impacts caused by extraction and processing of raw metal and ores. Credits are available in MR4.1, MR4.2, MR5.1, and MR5.2 for epoxy-coated bars as described in Sections 13.6.2.1 and 13.6.2.2.

13.6.2.1 Recycled Materials MR4.1 and MR4.2

The USGBC gives credits for building products that incorporate recycled materials. Meeting MR4.1 will provide one point, and meeting MR4.2 in addition to MR4.1 will provide an additional point.

Note for MR4.1 and 4.2: Information on the credits provided by epoxy-coated bars is available from your supplier. Generally, epoxy-coated bars are constructed using steel that contains over 97% recycled material from preconsumer and postconsumer sources. The application of the epoxy-coating adds virtually nothing to the total weight of the rebar and may be discounted. (With more than 70% combined recycled content, hot-dip galvanized steel also will easily meet the requirements of credits 4.1 and 4.2.)

13.6.2.2 Regional Materials MR5.1 and 5.2

The USGBC gives credits for building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation.

Note for MR5.1 and 5.2: As epoxy-coated bar suppliers are located near most major cities, in many cases, they qualify for credits in MR5.1 and MR5.2, depending on your particular project location. In determination of the manufacturing location, it is advised that the products are manufactured at the reinforcing bar fabricator, whereas the harvest location should be taken as the place where the steel billets are made.

13.7 SUSTAINABLE INFRASTRUCTURE

The concepts of sustainability discussed in this book are applicable to roads, bridges, and other elements of the infrastructure. According to the US Department of Transportation (Federal Highway Administration), as of 2012, the United States has 4.09 million mi. of public roads, including 47,714 mi. of interstate (world's second longest after China's), and 160,955 mi. of other National Highway System routes. According to the US National Bridge Inventory, in 2002, there were 596,800 bridges in the United States (Interstates supported approximately 60,000 bridges). Almost 26% (12.4% structurally deficient and 13.4% functionally obsolete) of the bridges in the United States are currently classified as either structurally deficient or functionally obsolete. Unlike the building sector, in the transportation arena, the structural engineer has more freedom in the selection of the form, type, and location of various elements of the infrastructure network and thus can exert greater influence in improving the sustainability of these elements (Mathur 2010).

Bridge deck deterioration is one of the leading causes of structural deficiency in bridges. All the strategies that are suggested for RC and steel reinforcement may be adopted for bridge decks also to make them sustainable. They include using supplementary cementitious materials such as fly ash and ground granulated blast furnace slag, recycled concrete aggregates or lightweight aggregates, thicker and denser covers, prefabricated components, epoxy-coated or corrosion-resistant rebars, and cathodic protection. In addition, *bidirectional post-tensioning* may be used to provide a permanent state of compression during service. Ferrocement stay-in-place forms will help alleviate corrosion and assist in accelerating deck construction. Wearing surfaces consisting of overlays made of asphalt concrete with a waterproofing membrane, high-performance concrete, silica fume-modified concrete, fly ash-modified concrete, polymer concrete, or latex-modified concrete have been used in the past to improve long-term service performance. Use of higher-strength concrete girders (55 to 80 MPa), higher-grade steel reinforcement (500 MPa and above), or high-strength beams/plate girders (340 to 520 MPa) will conserve virgin material. While designing members, all future possible widening/climatic conditions and deconstruction should be considered (Mathur 2010). It is very important to incorporate features and details that facilitate maintenance work.

Eliminating joints in bridges by adopting jointless bridges or using new joint systems with a longer service life can reduce the road closures needed for joint replacement and reduce emissions due to traffic congestion (Mathur 2010). In addition, special attention should be given to bridge deck drainage systems.

Life-cycle cost analysis of bridge infrastructure should consider all costs associated with extraction of natural resources, environmental impacts of manufacturing and final development, transportation costs, and decommissioning or reuse of the structure. Though the lowest life-cycle cost option is preferable, the project engineer should also evaluate the social, economic, and environmental aspects of the alternatives before selecting the final solution (Mathur 2010). A context-sensitive solution (CSS) must be adopted while planning and designing the bridge infrastructure (http://www.ite.org/css/RP-036A-E.pdf). The principles of CSS promote a collaborative, multidisciplinary process that involves all stakeholders in planning and designing transportation facilities and preserves scenic, aesthetic, cultural, historic, and environmental resources while maintaining safety and mobility.

More information on rebars may be obtained from the following institutes:

- Concrete Reinforcing Steel Institute—http://www.crsi.org
- Post-Tensioning Institute—http://www.post-tensioning.org
- Wire Reinforcement Institute—http://www.wirereinforcementinstitute.org

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14 Coatings for Creating Green Infrastructure

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CONTENTS

14.1 INTRODUCTION

The concept of designing structures for effective economical operation and maintenance is decades old. This idea can and should be one of the main themes of "green building" because it can effectively reduce the amount of resources consumed. This creates an opportunity for the construction industry as a whole to play a major role in the push toward green engineering, particularly because they consume a large fraction of energy and nonrenewable materials. The life cycle of a structure breaks down into three main phases where green principles can be applied: construction, maintenance, and demolition.

Any type of construction begins with the manufacturing of building materials. Currently, concrete is the most commonly used construction material with an estimated annual worldwide consumption of over 30 billion t. The manufacturing of Portland cement, the main component of concrete, annually produces over 500 million t of carbon dioxide emissions into the atmosphere since 2005.[1] This is projected to increase at a high rate as constructions in countries like China and India rapidly increase their consumption of concrete. Furthermore, the actual process of building these structures increases the emissions of greenhouse gases into the atmosphere created by transporting materials and utilizing large manufacturing machinery. Reducing the need for these materials is quite challenging considering the increasing world population, which, in turn, increase the need for more housing and transportation structures. One significant move toward creating green infrastructure is proper maintenance of newly built and even existing structures. Lowering the demand for new building materials will then result in less creation of harmful pollutants.

The maintenance of structures is the longest durational section of a structure's life cycle. Even routine maintenance consumes large amounts of resources, including capital, labor, and lost productivity due to inconvenience. Additionally, when repairs are factored into the equation, these consumption numbers increase greatly. In the United States alone, the concrete repair business is estimated at over $20 billion annually.[2] All developed countries now have a large inventory of aging infrastructures built with concrete that requires repairs to not only maintain their appearance but also more importantly ensure their structural integrity. There exists an opportunity to mitigate the need for these repairs, thus reducing the consumption of resources. Furthermore, this will increase their life cycle, lessening the need for demolishing and rebuilding existing structures.

This goal of creating green infrastructure can be achieved by fulfilling the following major objectives:

- Extending the life of existing infrastructures, thus reducing the need for repairs and rebuilding structures, improving their overall carbon footprint.
- Reducing the energy consumption of the structures during their lifetime.
- Enhancing the robustness of structures to resist natural and man-made hazards.

Recent advances in many different areas, including new materials, mechanical equipment, electronic controls, and automation, can be very effectively used to considerably improve the green aspects of structures. One of the most efficient ways to achieve these goals is by using high-performance protective concrete coatings. This chapter focuses on how using state-of-the-art coatings as surface applications can accomplish the goals of greatly improving the appearance, usability, and sustainability of various concrete structures.

14.2 CONCRETE MAINTENANCE ISSUES

Concrete is one of the most durable, economical, and sustainable building materials in the world. With proper mix proportions, placement, and curing, concrete structures that will last many decades can be created. However, the "perfect" concrete structure cannot always be created in the real world due to multiple controllable and uncontrollable factors. Furthermore, there are several environmental factors that affect the life of these structures, including harsh weather conditions, industrial pollution, and abrasion due to use of the structure.

The deterioration that occurs in these structures typically occurs at the exposed surfaces. This greatly affects the aesthetics of a structure as the surface becomes stained and discolored. Additionally, more serious types of deterioration can occur, including craze cracking and loss of surface cement mortar. This surface degradation can lead to major structural problems, such as loss of concrete cover resulting in reinforcement corrosion. Once the reinforcement is compromised, the surface deterioration not only affects the aesthetic appearance but also could result in structural failure. The most common method being used now to remedy these issues involves applying patching materials to affected areas, replacing elements of the structure, or in a worst-case scenario, replacing the structure entirely. However, these repair options are expensive, time consuming, and highly disruptive to the users of these structures who depend on them on a daily basis. The best way to lessen these issues is to properly protect these structures from the very beginning, mitigating the need for intrusive repairs. Slowing down this deterioration process will contribute immensely to the reduction of maintenance and repair cost while promoting an overall green building culture.

One of the most economical and direct approaches to preserve these concrete surfaces is to protect them from the environmental factors that cause deterioration. Durable coatings can be used for this purpose to preserve the pleasing aesthetics of concrete structures while also preventing structural deterioration, thus increasing the structure's life cycle.

14.3 CURRENT COATING SYSTEMS

Organic coatings have been used for several decades in construction and are used almost exclusively for both interior and exterior surfaces. They are broken down into two major categories: oil based and latex.

Oil-based paints have been widely used for centuries and have been lauded for their excellent adhesion, depth of coloration, ease of application, and versatility. They can be applied to almost any building surface with minimal surface preparation. However, they more recently have come under scrutiny for their environmental impact and are no longer the industry standard. Their drying and curing process produces a large amount of hazardous fumes that cause numerous health issues.[3] Furthermore, allowing for the completion of the drying process prevents timely utilization of these structures. Oil-based paints are therefore not considered green building materials and are being phased out of use in favor of latex-based paints.

Latex paints, also commonly referred to as water-based paints, make up the majority of paints being used in the marketplace. They do not provide the same level of adhesion as oil-based paints but work well with most substrates. They are also easy to apply, and because they are water-based, are easy to clean up as well. Considered to be closer to a green product, they are water-based and do not generate as significant an odor as oil-based paints during drying and curing. There are also several formulas of low-volatile organic compound (VOC) latex paints that are now readily available, though those offer some challenges with regard to application.

Both of these common paint types have their positive attributes but exhibit major drawbacks with regard to concrete structures. One major drawback is that neither of these paints is chemically compatible with concrete, forming only a weak mechanical surface bond. Additionally, organic paints form a film on top of concrete surface, limiting the free passage of water vapor. This water vapor will build up at the interface between the paint and the concrete, eventually forcing its way out. This limits their durability because they are much more likely to flake and peel off of concrete under normal use. Another effect of this film is that water can become trapped inside the concrete, eventually reaching the reinforcement. This can lead to corrosion of the metal, potentially creating major structural problems.

Although oil- and latex-based paints are the most widely used products on the market, there is still great potential for new innovative coating systems. This is particularly true for concrete, where there is still a market need for long-lasting and dependable coatings.

14.4 BACKGROUND OF INORGANIC COATINGS

Inorganic coatings are a relatively new advancement in the construction industry. Their uncommon properties, particularly their outstanding durability, create the possibility that they can fill the market need for advanced functional concrete coatings. However, their development is not without issues to successfully become a viable product in the marketplace. The major challenges facing the development of inorganic coatings include material sourcing, economic factors, ease of field application, and evaluation of long-term durability.

14.4.1 Material Sourcing

Material sourcing has always been a challenge in the construction industry. However, as the world has modernized, many of the hurdles for acquiring specialized materials have become much easier to clear. One specific example of this is finding materials that are microsized and nanosized. As little as 20 years ago, these materials required expensive processing that made it very difficult to acquire and use in the large quantities necessary for commercial construction. Since that time, processes have become more effective, efficient, and economical, making these materials much more widely available. Furthermore, technological advancement now moves at a global pace, so there exist several manufacturers producing the needed materials all over the world. This allows for the raw materials needed to produce inorganic coatings to be sourced locally, an important factor creating an environment of green building and sustainability. All of these modern advances allow for the manufacturing and sourcing of the best-quality raw materials to create optimally engineered inorganic coatings.

14.4.2 Coating Compositions

For the successful performance of inorganic coatings, there are many factors that must be fulfilled: ease of application and curing in field settings, chemical and mechanical bonding, and compatibility with parent surface to ensure long-term durability. Research over the past several decades has been performed to optimize these factors creating specific inorganic coating compositions.

Inorganic aluminosilicate coatings have been shown to encapsulate all of the necessary factors for quality application and long-term performance. Scientifically, aluminosilicates are very stable, and structures built with them have lasted for thousands of years. It can be seen that buildings built with good-quality clay bricks outperform similar buildings built with other materials, such as timber, steel, stone, and even concrete. There are many examples of this, including some of the first buildings built in the United States where bricks that are 400 years old are as good as new with sharp edges. Additionally, there are buildings built with bricks over 1000 years ago in Egypt that are still completely functional. Probably the best example of the longevity of aluminosilicates is the Chinese Terracotta Army, which is over 2000 years old.[4] The challenge becomes to integrate aluminosilicates into usable building materials. Concrete, steel, and timber are much more versatile and allow for the economical construction of large-span and complex structures that cannot be accomplished with pure aluminosilicate components. Therefore, the solution lies in creating a hybrid in which concrete is the durable core of a structure, while the aluminosilicate composition forms a protective shell.

Extensive research has been performed in this field to determine the optimal compositions for inorganic coatings. The results reported in this section present detailed information on the evaluation of a two-component liquid–powder inorganic coating system that best fulfills the aforementioned goals.[5] The cementitious part of this inorganic coating is a potassium aluminosilicate with the general chemical structure

$$Kn\{-(\mathrm{SiO_2}\,z - \mathrm{AlO_2})n\} \bullet w\mathrm{H_2O} \tag{14.1}$$

where $z \gg n$. The resin hardens to an amorphous (glassy) structure at moderate temperatures as low as 10°C, making it feasible for use in real-world applications.

14.4.3 Field Applications

The inorganic coating is prepared by mixing a cementitious liquid component with silica powder. Fillers and hardening agents can be added to the powder component. The two components can be mixed to a paint consistency using either a high shear mixer or specialized drill bits. Since the coating is water based, tools and spills can be cleaned easily with water. All of the components are nontoxic, and no fumes are emitted during mixing or curing. The pot life is a manageable 2–3 h ensuring easy application in field settings. Since the particle size of reacting solids is as low as 50 nm, this coating composition can cure at room temperature and become water resistant in less than 24 h. Its low viscosity allows for the common paint application methods of brushing and spraying to be used effectively. The inorganic coating has been successfully used on cement, concrete, steel, wood, and gypsum board applications.

The evaluations of inorganic coatings in outdoor field conditions have been performed in several different applications. These evaluations are of the utmost importance not only to determine the durability of the inorganic system in the real world but also to ensure that proper application can occur in actual field conditions. The focus of this section will be on demonstration done with the New Jersey Department of Transportation (NJDOT) and Rutgers University in the United States.

The primary objective of the field demonstration was to demonstrate the viability of inorganic coatings on large transportation-related surfaces encountered in transportation structures. The structure chosen was a retaining wall located at I-280 and Garden State Parkway in South Orange, New Jersey.[6] The surface consisted of a precast concrete with a surface area of about 700 m^2. The surface was in excellent condition and was pressure washed before the application of the coating in order to remove limited amount of dirt and possible precast form oil residue. The work schedule and the observations made during the execution of the coating procedure are described as follows:

- The application rate was about 20 m^2/person worker/day.
- The coverage was about 3 m^2/kg.
- Application was carried out using brushes and cloth rollers that provide deep penetration on the rough surface.
- The grooves were not coated, and this provided a pleasing brick-and-mortar appearance.
- The workers who applied the coating were comfortable with the process and did not have any difficulty even though they were not professional painters.

Details of the field demonstration project showed that the inorganic coating can be easily applied to large surfaces. The system is easy to work with and can be carried out using paint rollers or brushes, typically used for any coating application (Figure 14.1).

FIGURE 14.1 Application of inorganic coating to precast concrete retaining wall.

14.4.4 Durability Testing

There are several key factors that must be fulfilled to ensure long-term durability. One such factor is proper material compatibility, which is vital in several scenarios, including structural loading, thermal expansion and contractions, and wetting/drying. The "breathability" of the inorganic coating also becomes important when dealing with concrete. Concrete surfaces must be allowed to breathe to ensure the interface between the coating and the concrete to remain intact. Furthermore, water vapor release also prevents accumulation of chemicals brought by water that enters the structural elements through uncoated surfaces.

In order to evaluate the durability of the inorganic aluminosilicate composition, and the interface between the coating and the parent materials, ASTM C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing[7] was conducted using high-strength concrete beams reinforced with carbon fibers, using the inorganic coating as a bonding agent.[8] This test scheme, in which the strength contribution of carbon fiber is totally dependent on adhesive strength, provides information for both coating performance and durability of the coating/concrete interface. Results of this durability study showed that both the inorganic coating and the interface are durable under wetting/drying and freeze/thaw conditions.

Additionally, the field application performed on Route I-280 with the NJDOT detailed earlier has also been evaluated on a continuous basis to ensure long-term durability in the field. Monitoring has shown that the finished surfaces provided a long-lasting aesthetically pleasing appearance. An observation of the site 5 years after the application indicates very good compatibility with the parent material and resistance to deterioration (see Figure 14.2).

Having shown that the inorganic coating can meet the necessary requirements of economical material sourcing, easy field application, and excellent long-term durability, their use will look to increase throughout the industry as they become more widely available in the marketplace. Furthermore, attention can now be shifted toward the unique properties that only inorganic coatings can provide.

FIGURE 14.2 Inorganic coating evaluation 5 years after application.

14.5 ENGINEERED SPECIAL PROPERTIES OF INORGANIC COATINGS

There are several properties of inorganic coatings that are inherent to their chemical composition. These include “green” properties, abrasion resistance, fire resistance, water resistance, phosphoric capability, and self-cleaning properties.

14.5.1 Green Properties

Green properties in building materials are of utmost importance for the continuation and development of sustainable structures. An important aspect of this overall approach is to preserve the health of the individuals who both work on these structures and reside in them. One of the major organizations that monitor these types of products and develop certifications is the United States Green Building Council.[9] They provide several different levels of certification through Leadership in Energy and Environmental Design, better known as LEED certification, to identify products and buildings that encompass the principles of green building. Inorganic coatings qualify for LEED since they contain zero percentage of VOCs because they are water based. The majority of coatings contain a solvent that contains harmful components, whereas inorganic coatings’ solvent is simply water. This greatly reduces the health risks during coating applications. Furthermore, because water is the only by-product of inorganic coatings during drying and curing, there is virtually no odor allowing users to occupy the coated structures with minimal delay.

14.5.2 Increased Safety

Another favorable aspect of the inorganic coating that increases overall safety is the fire-resistant property. Because the inorganic coating does not contain any organic components, there is no part of the coating that is flammable. The inorganic coating testing has shown that it can withstand temperatures up to 1000°C with no change to the coating surface.[10] During a fire, people are most negatively affected by the toxic smoke and fumes generated by burning organic materials, such as paint, furniture, carpeting, etc. This inorganic coating does not create harmful fumes, even at very high temperatures, and has a flame spread index of zero. This property greatly reduces the hazard that the inhabitants of a structure experience during a fire.

Inorganic coatings can be used as a protective sealer to increase the life cycle of structures subject to high-moisture environments. Water presents many problems for concrete structures as it creates leaks that over time cause problems for building inhabitants and can even result in structural damage. Salt water especially can create serious structural issues for bridges and tunnels as the embedded rebar can corrode quickly under these conditions.[11] Inorganic coatings can be used to protect these structures, such as bridges and tunnels, from salt-water ingression. Since inorganic coatings form a chemical bond as well as mechanical bond with concrete, the surface permeability is greatly reduced resulting in less moisture being absorbed. Additionally, inorganic coatings contain materials that are high on the Mohs scale of hardness making them resistant to abrasion. This property increases the surface strength of exposed concrete, reducing the amount that they will chip, crack, or spall, which also reduces the amount of damaging water being absorbed by the structure.

The chemistry of inorganic coatings allows for the addition of many different types of functional fillers. One of these fillers that can be used to greatly increase the safety of structures is a phosphoric fluorescent (glow-in-the-dark) pigment. Phosphoric pigments are "charged" when exposed to any ultraviolet (UV) light, such as sunlight or car headlights, and hold that energy until it becomes dark.[12] When the surroundings become dark, this stored energy is re-emitted as light. This can be used in dark areas for better structural illumination, such as retaining walls and highway dividers. Additionally, it can also be used in areas that become dark when power failure occurs. Hallways, stairwells, and other escape routes used during emergencies can easily be illuminated, helping to lead inhabitants to safety out of structures that need to be evacuated.

14.5.3 Self-Cleaning Property

The most unique property that can be incorporated into inorganic coatings is created by additives that form a self-cleaning surface. Every day, the environment is contaminated and polluted by fossil fuels burned off by cars and factories, as well as dust and mold from natural processes. These soiling particles deposit themselves on concrete structures, creating surface deterioration, causing spalls and cracks, and making them unsightly. To counteract this, inorganic coatings can incorporate photocatalytic materials that will self-clean their surface. This self-cleaning property can be used to slow down the above-mentioned deterioration mechanisms. The self-cleaning compound breaks up the organic impurities settled on the surface by using UV light. These compounds cannot be used with organic formulations because they will degrade the binders in the paint. Inorganic coatings do not contain these binders, allowing for the coating to remain durable while creating an effective self-cleaning surface.

The self-cleaning property was evaluated using a protocol developed in Europe.[13] In this test, Rhodamine B dye was applied to a coated surface, and the dye's deterioration was measured during exposure to UV light over a 48-h period using a color meter. Figure 14.3 shows that the dye quickly deteriorates exponentially in the first hour and then continues to deteriorate until the dye was fully removed.

Self-cleaning is a very valuable property of inorganic coatings for building construction by reducing the maintenance costs of structures. For multistory commercial and residential buildings, private residences, and manufacturing facilities, one of the major tasks in maintenance is to keep the exterior building surfaces defect-free and maintain nice aesthetics. Their exterior surfaces have to be painted every 5 to 10 years and constantly have to be cleaned to prevent damage to the parent surface and improve their appearance. Using the inorganic coating as a surface that cleans itself using sunlight and rain is a major advantage in the battle to maintain structures.

Along with keeping surfaces clean, the self-cleaning property can also be used to depollute the environment. Large surface areas of structures can be used to convert NO_x to nitrogen and oxygen using sunlight as the energy source. Therefore, the opportunity exists to convert concrete jungles to concrete forests by converting air pollution into less harmful substances.

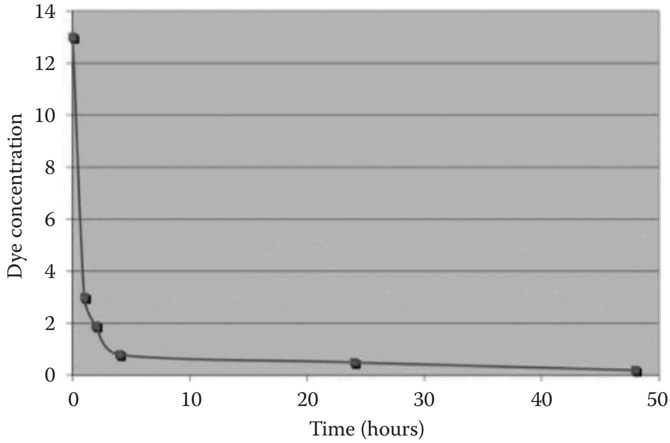

FIGURE 14.3 Rhodamine B dye concentration deterioration over a 48-h period.

14.6 MARKETABLE ASPECTS AND COMMERCIAL APPLICATIONS

Enumerated throughout this chapter are the valuable properties that inorganic coatings can provide to concrete structures. There are also several properties of these coatings that make them ideal for easy use in commercial applications. Necessarily the most important aspect to first consider with regard to inorganic coatings is their manufacturing cost. As described previously, there have been significant reductions in the cost of raw materials that comprise these coatings. This fortuitous development allows for manufacturing inorganic coatings at a price similar to high-end latex paints, currently the most widely used coating system. This allows for companies manufacturing inorganic coatings to remain competitive in the market place and create the profits necessary for creating a sustainable business model.

One important aspect for any coating product is to create the proper aesthetics for the end user. Since the base coating material is white, it allows for other color schemes to be easily formulated using inorganic pigments. This creates a broad spectrum of color options that can match whatever the consumer is looking for. Additionally, because inorganic coatings have a greater thickness than typical coating products, they can be manipulated to create unique textured surfaces. Inorganic coatings provide the color flexibility and surface requirements for nice aesthetic construction.

Inorganic coatings provide great value when used with cement and concrete structures because of their compatibility. One of the most common materials used for finishing the surfaces of buildings is plaster. Inorganic coatings can be used on plaster to create long-lasting colors as well as provide water protection to the structure. Additionally, in modern construction, there are many new building materials available.

Aerated concrete has been in use for decades around the globe and has greatly increased in use recently. It offers many great properties for construction because it is lightweight, provides excellent thermal insulation, and can easily be modified on site.[14] These special features allow for economical building, as well as lowering the consumption of energy for maintenance and temperature control. Inorganic coatings work very well with aerated concrete blocks by decreasing their surface permeability, preventing water from getting into structures. This new type of building system is only one of many new methods.

Precast construction and ferrocement construction have become much more widely used methods for large building projects. These types of construction rely on concrete components being manufactured in a factory setting. This allows for complete control over mixing, pouring, and curing conditions creating the most optimal structural elements. Inorganic coatings can also be easily applied in the factory at the time of manufacture, greatly reducing labor and wasted material costs. Additionally, because they form a protective shell, they will also prevent damage from occurring to these precast elements during the shipping and building process.

14.7 SUMMARY

Concrete construction remains the major method of building. Even though this has been the preeminent building material for centuries, there are still several challenges in erecting, maintaining, and protecting these structures. Therefore, there exists an opportunity to discover and create state-of-the-art solutions to these commonly found issues. Cutting-edge solutions require cutting-edge materials, including nanomaterials and micromaterials. The increasing availability of these materials has made it possible to create state-of-the-art solutions, such as functional inorganic coatings. Inorganic coatings are an economical and easily applicable solution that can be used to increase the life cycle of these structures, thus moving forward the green building culture.

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15 Materials' Specifications *The Missing Link to Sustainability Planning*

Chetan Hazaree

CONTENTS

15.1 INTRODUCTION

This two-part chapter initially talks about sustainability and its role right from the planning stage. Questioning the way we misuse sustainability, part A of this chapter deals with describing the importance of its practical implementation in construction. Further, the role of planning for sustainability is emphasized from the national policy level down to construction and operational maintenance levels. Stating the pivotal role of construction materials, part B of this chapter deals with fly ash. In this part, fly ash is described as a well-known and deeply understood yet poorly utilized material. Drawing examples from real-life projects, standards, and specifications, this part clearly establishes how proper utilization of materials through adequate changes in the design, specifications, and construction process could easily enhance the sustainability footprint of concrete as a material.

15.2 PART A: PLANNING FOR SUSTAINABILITY

15.2.1 Sustainability: A Jargon?

In recent years, sustainability has rapidly become a common word in most sectors, construction being no different. Albeit broader definitions of the term are available, and everyone wants to embrace "the term," in general, there seems to be lack of mechanism of implementing sustainability in a systematic and objective manner. Often myopically understood and superficially addressed, for many, it is confined to reporting only. The fact of the matter, however, is that it is one of the most pressing human problems that needs to be addressed right from the policy level to implementation on the ground. Each individual acting as a stakeholder is eventually accountable for delivering—after all, we are accountable to not just respective nations but also our future generations. Apparently, it is worth pondering whether what we call development really is development or not.

Whether defined in terms of social or engineering definitions, sustainability in a broad sense covers ecological, economical, and social sustainability; each of these pillars needs proper practical address. Some definitions include culture as a part of sustainability. Efforts for achieving sustainability have to be seen holistically and cannot just cover one aspect of it while ignoring others. This could create imbalance at either the microlevel or macrolevel or both. For example, energy-based optimizations alone cannot become the basis of sustainability. For the construction industry, sustainability portrays a complex picture—unattended to and not completely understood. Increasing level of fragmentation and consequent complexities further enhance the difficulty in "characterizing sustainability."

15.2.1.1 Sustainable Construction

Sustainable construction aims to meet present-day needs for housing, working environments, and infrastructure without compromising the ability of future generations to meet their own needs in times to come. It incorporates elements of economic efficiency, environmental performance, and social responsibility [1]. A truly sustainable construction project needs to include not only social considerations for the final users but also considerations such as the project's impact on the surrounding community and the safety, health, and education of the workforce. Integrating these considerations will improve both long-term project performance and the quality of life for those affected by the project [2].

Sustainable construction [1] thus involves issues such as

- The design and management of buildings
- Material performance
- Construction technology and processes
- Energy and resource efficiency in building, operation, and maintenance
- Robust products and technologies
- Long-term monitoring and adherence to ethical standards
- Socially viable environments and stakeholder participation
- Occupational health and safety and working conditions
- Innovative financing models
- Improvement to existing contextual conditions
- Interdependencies of landscape
- Infrastructure, urban fabric, and architecture
- Flexibility in building use, function, and change
- The dissemination of knowledge in related academic, technical, and social contexts

According to the United Nations Environment Program (UNEP) [3], sustainable building and construction should have the following characteristics:

- Routinely designed and maintained to optimize the entire life span.
- Sustainability considerations and requirements should take in building legislation and standards.
- Environmental aspects should be considered in the project and should include short-term as well as long-term aspects.
- Policies and incentives provided by the government to support sustainable building and construction practices.
- Investors, insurance companies, property developers, and buyers of buildings are aware of sustainability considerations and should take an active role to encourage sustainable building and construction practices.

It is critical to understand that aligning changes with sustainability is an integrated responsibility of all involved in the value chain. The drivers for such change are not just of national interest; these are also in the interests of a responsible individual. While there seems to be broad understanding of sustainability, it has not percolated into our practices at various levels. *It is crucial to make sustainability part of our lifestyle* and not just restrict it to policies and procedures. Such a change is really essential and it is only through this that sustainability will be able to make a meaningful impact.

15.2.1.2 Understanding the Scales

Looking at the way construction is expanding, the ways in which we will live, commute, transact, and manage our energy and natural resources will be gradually changing. Small changes would make large impacts. Hence, it is important to appreciate the impact of "small change." Additionally, the scales at which sustainable changes are made are also critical. Our ability to deliver sustainability is very closely linked with our ability to understand materials at very small scales. Figure 15.1 [4] demonstrates this fact. For such changes to happen and be realized, a coordinated effort is required at various levels of decision making. This will involve owners, contractors, materials' manufacturers, governmental agencies, end users, and standardization bodies, to name a few.

15.2.2 Sustainability Planning

Planning for sustainability will not happen at a project or individual level. It has to take a top-down approach wherein international changes influence changes at the

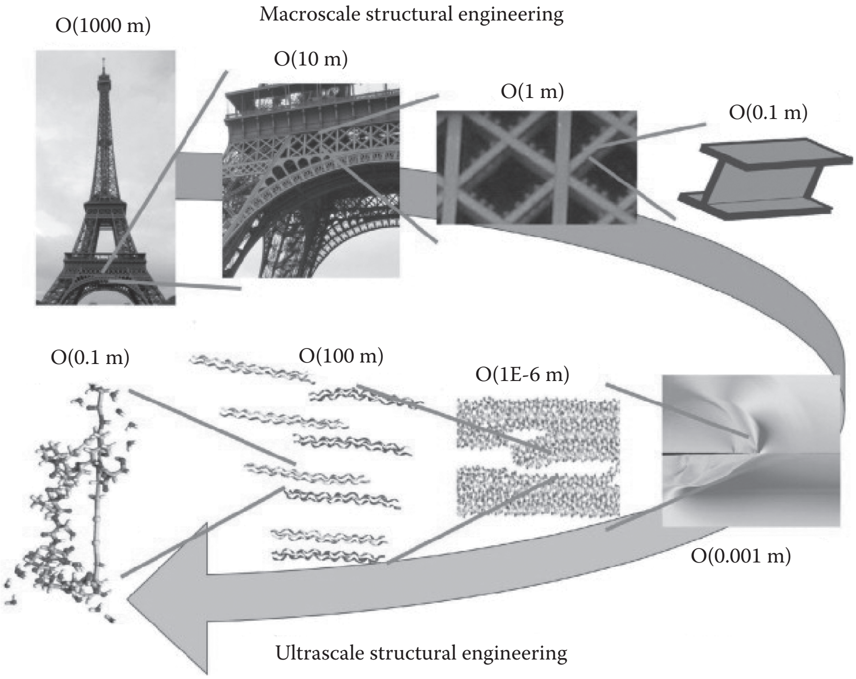


FIGURE 15.1 The long-term impact of our work is that it will extend our ability to perform structural engineering from the macroscale to the ultimate scale—the nanoscale. Opening the material scale as design space for new material development may lead to endless possibilities. (From Buehler, M J and Ackbarow, T, *Materials Today*, 10, 9, pp. 46–58, 2007.)

national level. And through policy changes and standardizations, projects are influenced. Sections 15.2.2.1 through 15.2.2.4 discuss changes required at the industry and project level for achieving sustainability.

15.2.2.1 Changing the Industry

The construction industry is one of the most dynamic, risky, and challenging business sectors. There is much waste, and it encounters problems caused by myopic control [5,6]. Considering the size and importance of the construction industry to the world economy and its contribution to environmental damage, the suggestion has been made to use the emerging "sustainability" agenda as a lens through which construction performance can be measured [7]. With developments happening in the fields of computing, equipment, and material development, time is rife for the construction industry to change. This change will have to take place at multiple levels while taking into account the factors that plague its growth (Figure 15.2).

15.2.2.2 Project Life Cycle

Typical project life cycle phases are shown in Figure 15.3. If sustainability is to be cultivated and made a lifestyle, then it has to begin from the concept design stage. At each level in a project, sustainability thought needs to be built in as an integral part of the process. For example, material specifications can be so drafted that sustainable materials would be easily selected and used. Similarly, the construction methodologies can select methods and techniques that lead to sustainability.

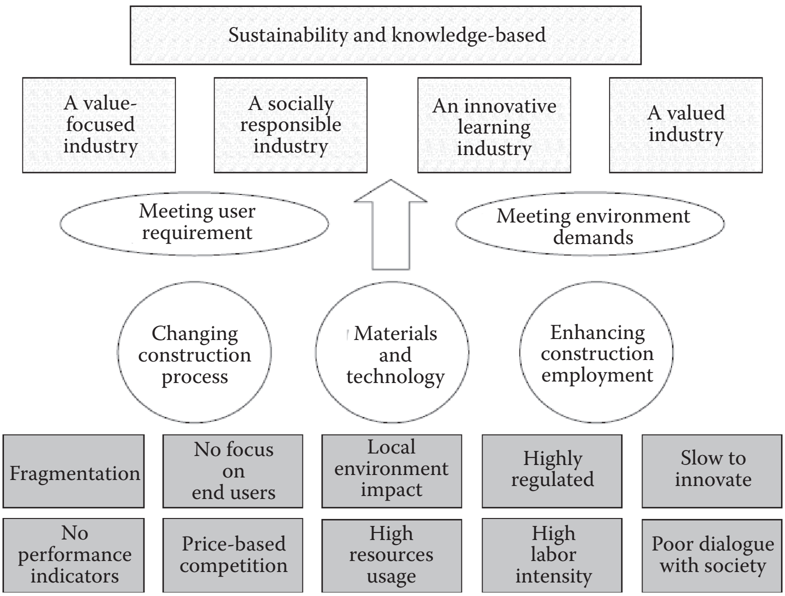


FIGURE 15.2 Conceptual framework for making construction industry sustainable and knowledge based.

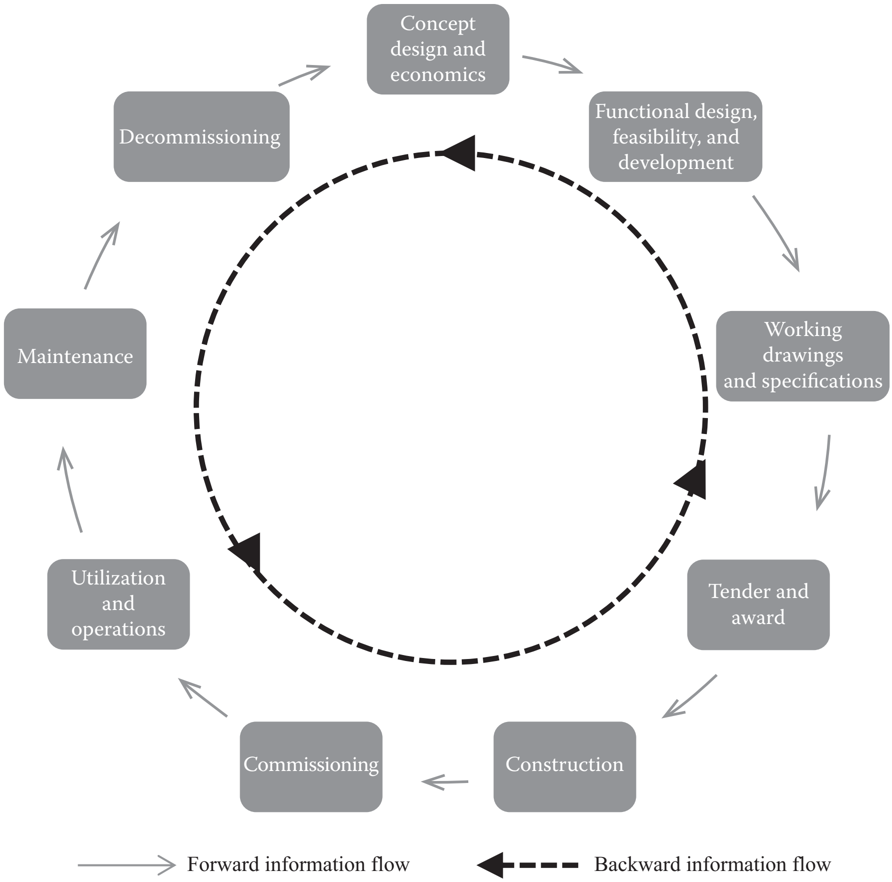


FIGURE 15.3 Typical project life cycle phases.

For sustainable construction, durability of that structure would be of extreme importance. One of the most important durability parameters is design life, yet this is not always clearly identified in codes, and specification and definition are not always clear and consistent. Figure 15.4 provides clearer definitions. The term "design life" is often used to convey the same intent as "design service life," and both terms are acceptable to convey the same intent. It is the period in which the required performance shall be achieved and used in the design of new structures' construction. Service life (operational), however, is the period during which the required performance of a structure or structural element is achieved, when it is used for its intended purpose, and under the expected conditions of use. It comprises design service life and prolonged service lives [8]. It is worth noting that the performance of a built structure will depend on the design, the materials selected, the construction processes used and operational conditions, and the maintenance strategies adopted. A careful balance is often required while estimating the life cycle cost analysis [9]. For example, a costlier material or design may cost more initially but could drastically reduce the maintenance cost.

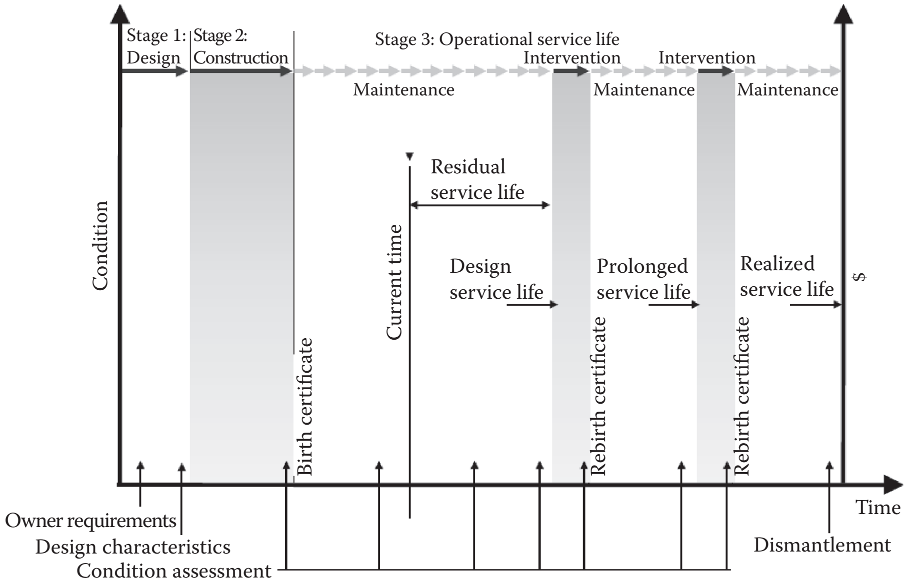


FIGURE 15.4 Project life phases. (From Mills, A, *Structural Survey*, 19, 5, pp. 245–252, 2001.)

15.2.2.3 Planning for Sustainability

A formal process for achieving sustainability of built structures through project conceptualization, specifications, design, construction, and operational maintenance is missing. Sustainability can be provided with improved confidence when the asset owner is actively involved and is clearly laying down the sustainability targets. In engineering terms, sustainability planning would involve cost-effective selection and usage of materials combined with design processes, construction methods, and detailing to achieve required service life without untimely operational maintenance and while dealing with the social and ecological context of the project. This could be done at various levels—international, national, state, local, and project level. Each of these levels should be properly aligned.

The sustainability planning should initially appeal to the owner; only then will it be successful. Implementing such change either in a government or private sector would need some impetus and encouragement, a proper mechanism that needs to be worked out. A carefully crafted sustainability plan should actually benefit all the stakeholders in a project including the nation at large and the owner, designer, consultant, general contractor, and operators of the project.

15.2.2.4 Holistic Approach through Stakeholder Involvement

The increasing level of fragmentation in construction projects has fostered its complexity, raising the significance of rigid coordination that assures high level of integration among stakeholders (demand and supply sides) if the project is to be successfully completed. In addition, close interaction with suppliers necessitates information flow, cooperation, openness, and transparency [10]. Stakeholders are classified as

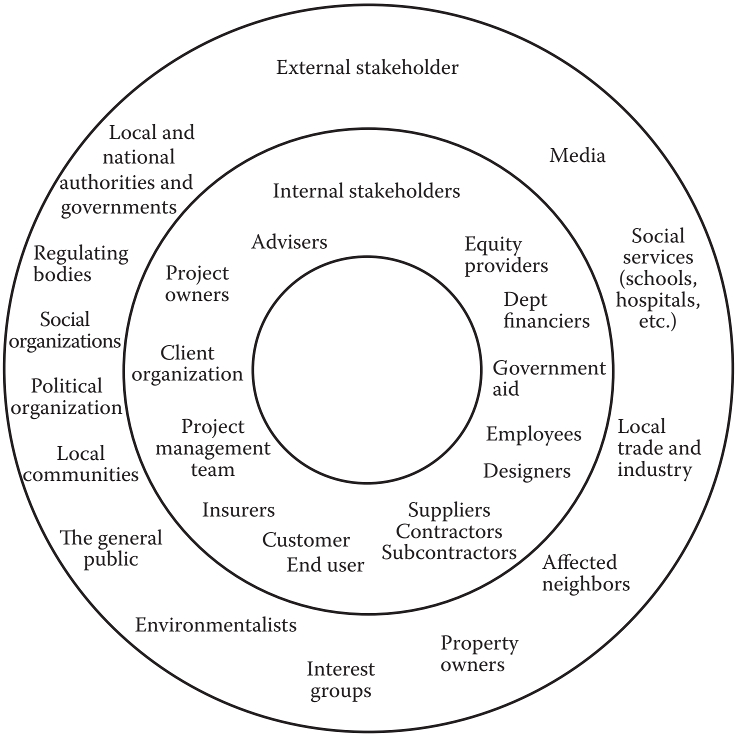


FIGURE 15.5 Stakeholders in a construction project. (From Cleland, D I, *Project Management—Strategic Design and Implementation*. New York: McGraw-Hill, 1999.)

internal, i.e., those who are formally connected with the project (e.g., owners, customers, and employees); and external, i.e., those affected by the project in some way [11]. Figure 15.5 demonstrates the stakeholders involved in construction. For a construction project to become sustainable, the stakeholder involvement has to be critically managed right from the conceptualization stage of the project [12].

The topic of stakeholder management is to be addressed at a variety of levels and complexities. Before the concept trickles down to the project level, it has to be implemented at the international, wherever applicable, and national levels so that projects could be executed in a seamless manner. For example, before undertaking a megaproject, clearances from environmental agencies would imply swift delivery at the construction stage. Similarly, if all the stakeholders are properly aligned through the required degree of communications, sustainability can also be achieved in a systematic manner.

15.2.3 Pivotal Role of Materials

The construction industry is consciously growing in its understanding of achieving sustainable construction. However, this needs to be realized in practice through various means and mechanisms, which is a complex task and involves balancing multiple faculties of human understanding. Materials play a pivotal role in satisfying the requirements of holistic sustainable construction. The following is a sampling of factors influencing material sustainability:

- Ensuring appropriate selection of materials
  - Functionality
  - Quality
  - Availability—today and tomorrow
  - Recyclability
  - Waste utilization
  - Durability and long-term performance
- Lower embodied energy
- Compatibility with overall systems
- Costs—today and tomorrow
- Impact on ecology and cleaner use and adoption
- Impact on culture

The pool of construction materials has more or less remained the same over many years—use of supplementary cementitious materials, for example, has changed the way we are able to work with concrete. Albeit concrete seems to be a greener choice (see Table 15.1), its availability vis-à-vis cost is critical in deciding its global acceptance.

15.2.3.1 Natural Resource Planning—Our Limited Choices

Developing nations are busy targeting ambitious plans for infrastructure development. These plans, however, need sustainability thinking; else at the cost of today's convenience, we would cause great inconvenience for tomorrow. For sustainability to be realized in a systematic manner, planning of the national natural resources is essential. Creating large and megaprojects appears to be very lucrative in pushing the economy, but is it a sustainable push? For example, on an average project, it is not uncommon to have 0.7–1.0 million m^3 of concrete implying easily 245,000–350,000 MT of cement consumption, which in turn implies 31,850–45,500 MT of CO_2 generation. Similarly, such a project would easily involve 1.7–2.5 MMT of aggregates.

TABLE 15.1
Embodied Energy and Associated CO_2 Emissions from Common Construction Materials

Material	Embodied Energy (MJ/kg)	CO_2 (kg CO_2/kg)
Normal concrete	0.95	0.13
Fired clay bricks	3.00	0.22
Road and pavement	2.41	0.14
Glass	15	0.85
Wood (plain timber)	8.5	0.46
Wood (multilayer board)	15	0.81
Steel (from ore)	35	2.8

At any given point of time, such multiple projects are going on—the impact could be unimaginably catastrophic if something is not done now.

This national resource planning is critical in designing and developing cements for tomorrow, which have to be along the lines of the constituents of earth. Along the same lines, the use of utilizable supplementary cementitious materials is also essential. Large amounts of fly ash and pond ash dumped due to nonconsumption will be wasted causing nuisance. In the same way, quarrying for aggregate manufacturing and dredging in rivers and seas are issues that should be taken at the project conceptualization stage; only then will there be coordinated effort in realizing sustainability.

15.3 PART B: SUSTAINABILITY AND FLY ASH SPECIFICATIONS

This part of the chapter provides an example of fly ash and how its sustainability potential is underutilized. The scientific community and construction fraternity around the world have been researching, testing, and applying fly ash concrete technology for decades. However, the current state of the practice in India is inadequate and not commensurate with the voluminous generation of coal ashes in general and fly ashes in particular. If the technology is tested both in laboratory and field, then an obvious question that arises is why there is only limited use of fly ash. On one hand, sustainability is extensively and openly deliberated. There is in general a consensual understanding of the implications of not using coal ashes; there is availability of fly ash, and yet on the other hand, the consumption of fly ashes is surprisingly low. Section 15.3.1 analyzes and presents a perspective on the gaps preventing adequate consumption of fly ash (and coal ash) in concrete.

15.3.1 Longevity of Fly Ash-Based Concretes

Research and practice have established fly ash as a sustainable, cost-effective, and workable ingredient for making concrete. Fly ash's ready and generous availability and associated operational ease have made it a pozzolanic material of choice. Moreover, the benefits that fly ash-based concretes offer in terms of fresh properties, strength development, and durability have made fly ash's inclusion in contract specifications of various government and private agencies routine. Despite this wide-scale acceptance and inclusion in projects of varied nature (from housing to heavy infrastructure), the specifications are impeding the full-scale and mature benefits of sustainable usage of fly ash.

Concrete incorporating (low-calcium) fly ash, in general, is known to have a retarded strength gain in the initial period while having an extended period of strength gain as long as the pozzolanic reaction takes place. This period of extended substantial reactions resulting in denser pore structure and hence other consequent benefits can be as long as a year and occasionally more. Research has established the immediate, long-term, and sustainable benefits of fly ash concrete technology including high-volume fly ash concrete (HVFC) and high-performance, high-volume concrete (HPHVC). With the advent of polycarboxylate (PC)-based admixtures, the limitation with regard to early-age concrete properties (lower strength) of fly ash concrete is also being reduced.

15.3.2 Contemporarily Unscientific Craze for 28-Day Strength

As commented by Neville, the use of 28-day strength for characterizing concrete seems to have acquired an immutable position with compliance, with the specification being almost invariably laid down in terms of the 28-day strength [13]. Compliance to such specifications becomes a contractual matter that is extremely difficult to dispute and revise at a later stage. The difficulty arises because construction specifications, if not argued and scientifically changed at the bidding stage, need to be followed like unchangeable laws, and actual physical construction is often the penultimate stage of a project life cycle. Any change related to sustainability has to be built in from the project conceptualization stage; construction is often a stage where the thinking process is reduced to minimal, except for the construction methodology part.

15.3.2.1 Definition of Characteristic Strength

The minimum, probabilistic definition of characteristic strength is widely accepted. As defined in IS 456, the characteristic strength of concrete is defined as the strength of material below which not more than 95% of the test results are expected to fall [14]. It is actually the lower characteristic strength. It is important to note that this definition ignores the testing age of concrete. On the other hand, IS 10262 [15] considers the characteristics of compressive strength of concrete at 28 days, and the same is used in describing the grade of concretes in Table 2 of IS 456 [14].

It is worth noting that IS 456 in its clause no. 6.2.1 (increase in strength with age) states "there is normally a gain of strength beyond 28 days. The quantum of increase depends upon the grade and type of cement, curing and environmental conditions. The design should be based on 28 days characteristic strength of concrete *unless there is evidence to justify a higher strength for a particular structure due to age*."

In practice, during the construction stage, the above clarification is rarely accepted in contracts once a contract is signed, and changing of specifications midway (while being cognizant of its implications) is rarely an acceptable practice. The definition of characteristic strength, however, needs to be carefully applied when specifying later age acceptance of concrete strength.

15.3.2.2 Long-Term Strength Gain—Unused Sustainability

As is well established, fly ash concretes continue to gain strength over a relatively long period of time. Projects are to be completed in a stipulated period of time. There are, however, two important points to be considered, viz., the age at which a structure or its component is subjected to its first design load (if at all) and what the other construction loads are that a structure or its component has to bear before such loading. The construction specifications (not the general technical specifications) should ideally be prescribed while tying this fact in with the feasible construction schedule. Now, let us look at a couple of cases where appropriate change of rather restrictive specifications would make the construction more sustainable.

Consider the examples of mixes cited in Table 15.2. The strength development of these concretes with control mix is shown in Figure 15.6. In the first case (Figure 15.6a), the fly ash mix is proportioned using a 28-day strength equivalence achieved through reduction of water/binder (w/b) ratio and increased admixture consumption with respect

TABLE 15.2
Comparative Mixes with and without Fly Ash

Type of Mix	OPC (kg/m³)	PFA (kg/m³)	Binder (kg/m³)	W (kg/m³)	w/b	Adm. (kg/m³)	Cement Savings (kg/m³)
OPC (control)	300	0	300	160	0.53	3.5	–
OPC + fly ash (28-day equiv) (A)	220	115	335	155	0.46	4.2	80
OPC + fly ash (56-day equiv) (B)	195	105	300	155	0.52	3.5	105

Note: OPC, ordinary Portland cement; PFA, pulverized fly ash.

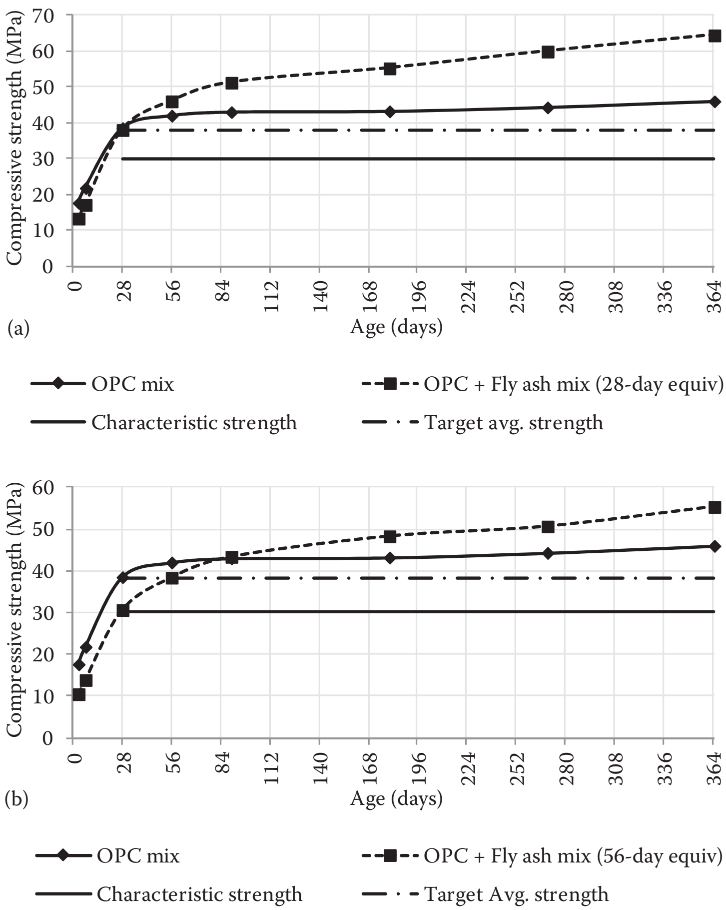


FIGURE 15.6 Comparative strength development of mixes—effect of equivalent characterizing age. (a) Mix based on 28-day and (b) 56-day characterizing strength.

to control mix. The early-age strength is relatively lower than the corresponding control mix. The strength and other properties are tested only through 28 days. Although use of this mix reduces the cement consumption, due to 28-day characterizing strength, the beneficial effects of fly ash, which actually come beyond 28 days, are not harnessed.

In the second case (Figure 15.6b), the fly ash mix is proportioned using a 56-day strength equivalence achieved through reduction of w/b ratio with respect to control mix. In this case, the early-age strength is relatively much less than the corresponding control mix. The strength measurement is done through 56 days, a little improvement than the first case, but still away from sustainably optimal usage of cement and fly ash. So how does this impact the mix design? Refer to Figure 15.7; longer characterizing age would increase the strength, and there could be cases where a concrete of certain grade can be categorized as a concrete of higher strength at a later age. Moreover, the benefits that manifest after the specified characterizing age are ignored contractually and from the sustainability point of view. Hence, for fly ash-based mixtures, the characteristic strength should be defined at practically the possible longest age.

Let us look at an example where the concept of long-term strength gain is practically and effectively applied, viz., roller-compacted concrete dam. Refer to Figure 15.8, where a typical field cube-based strength development plot for medium-paste roller-compacted concrete (RCC) concrete is shown. In the case of dams, both from material and construction points of view, it is possible to wait for long periods before the required characteristic strengths are achieved. The use of long-term strength for dam concretes has been effectively used in other countries with the characterizing age ranging between 1 and 2 years. Considering various loadings, the maximum stresses under load do not usually develop until the concrete is at least 1 year old [16].

15.3.2.3 Construction Impact of Age, Examples

Let us look at cases where other than 28-day strength characterization is often used due to demand of construction schedule, resource management, time cycle requirements, etc. Let us first consider early-age strength requirements. Consider prestressed concretes, for example. The strength is monitored on a daily (sometimes hourly) basis until the

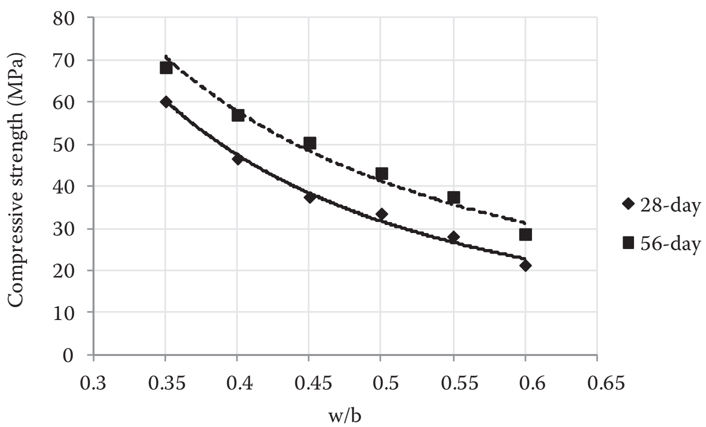


FIGURE 15.7 Effect of age on characterizing strength. Fly ash content at 35% of the binder.

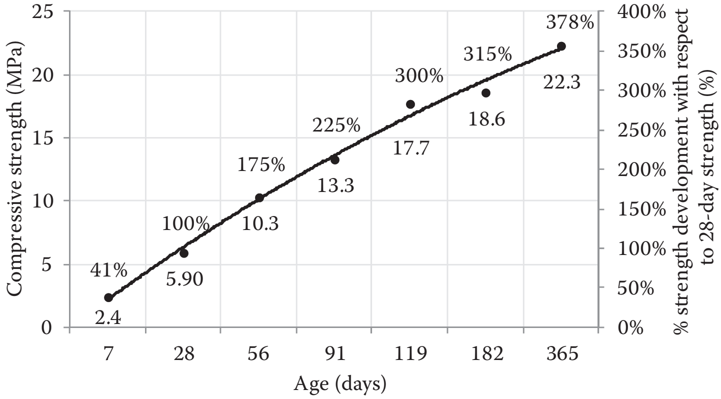


FIGURE 15.8 Strength development in a typical RCC dam concrete; OPC: 75 kg/m^3, fly ash: 145 kg/m^3, and w/b: 0.57.

concrete reaches the required tolerable prestressing strength. Another example is that of tunnel lining—either with segmental jump form or fixed form. In this case, the required formwork stripping strength governs the strength and hence the selected mix proportion. Similarly for columns, stripping of formwork subtly governs the mix design rather than the 28-day characteristic strength. Usually, in such cases, the specified 28-day strength is exceeded by substantial margins—one or two levels higher. For example, a 35-MPa specified concrete may end up having 45–50 MPa 28-day strength when designed with OPC. A reason for this happening is the conservative approach to mixture designs; a holistic approach would produce more economical and sustainable mixtures.

Now, let us look at cases where the strength development could be altered or delayed. With fly ash concretes designed for equivalent-to-OPC performance, the early-age strength could be delayed; however, the 28-day strength may remain the same as OPC concrete. This method of mixture proportioning often restricts the cement replacement levels of fly ash, thus reducing the sustainability potential of such concretes. Examples of such alteration in the strength development profile, while maintaining equivalent 28-day performance, include mixes used for slabs, restrictive specifications for (mass) mat foundations, and spillway structures, among others. And then there are clear cases like mass concretes, dam concretes (conventional concrete dam, RCC), and structures not exposed to prompt loading, where the characteristic strength achievement could be delayed for longer periods ranging between 56 and 365 days or even beyond.

In summary, with more concrete being made with fly ash (and/or other supplementary cementitious materials), we need to rethink 28-day strength and its limitations from the sustainability point of view. It is therefore essential to draft flexible specifications while remaining cognizant of the overall construction program, complete design and engineering of structures, and, above all, long-term sustainability. This in turn, requires a highly integrated approach for introducing sustainability right from the project inception stage. An approach worth considering is delivering the required strength at an age when it is actually required (perhaps in phases), i.e., loading-dependent strength delivery. A challenge with this approach is to decide, *prima facie*, what should be the thresholds for such age and load-dependent delivery and framing of criteria for acceptance of strength (or other index) for payments with sufficient reliability. The consistency of fly ash and hence of the properties of concrete incorporating such fly ash is an essential element for consideration in this regard.

15.3.3 Indian Coal Ashes, A Prospective Scenario

Fly ash used in India is generated from the use of high ash content (25%–45%) sub-bituminous, bituminous, and/or lignite types of coal. Typically, the calorific value of coal ranges between 3850 and 4250 kcal/kg with a carbon content ranging between 39.3% and 60.2%. On the other hand, American coal has calorific values ranging between 6378 and 7728 kcal/kg with carbon content ranging between 64.2% and 72.4%. Due to the characteristic nature of coal, the fly ash available in India is of low lime type (class F as per ASTM C618) except for a few cases where class C fly ashes are also available, like Surat, Mumbai, etc. Table 15.3 shows a sampling of various fly ashes in India.

The reactivity of fly ash with cement is intrinsically known to be affected by inherent characteristics of the fly ash, viz., chemical and mineralogical composition, morphology, fineness, and the amount of glass phase. The glass content of Indian fly ashes ranges between 20% and 30%, which is very low compared to fly ash from the United States, Japan, and France where the glass content is as high as 80% or even more [17]. Moreover, the reactivity of the fly ashes is also a function of the basic coal ash, as well as the type and efficiency of boilers where these are burnt. The glass content is more of a function of burning efficiency of the boilers. Apart from the type of coal and the coal burning process used, the quality of fly ash captured inside a thermal power plant may vary in character from one location to another due to changes in furnace conditions and the type of collecting system.

15.3.4 Challenges with Fly Ash Concretes

15.3.4.1 Variability

Variability in fly ash is inevitable as it is a byproduct, mostly termed as waste by those involved in its generation. Often, variability is caused by one or more of the following factors:

- Inconsistent burning different coals or blends of coal or use of oil as a supplementary fuel
- Use of other fuels blended with coal
- Use of precipitator additives, such as ammonia
- Collection of ash from
  - Start-up or shut-down phases of operation
  - Plants not operating at a "steady state"
  - A peaking plant instead of a base loaded plant
- Ash that is handled and stored using a wet system
- Improper ash handling system with no or minimal supervision
- Variations in the burning processes

TABLE 15.3
Sampling of Indian Fly Ashes

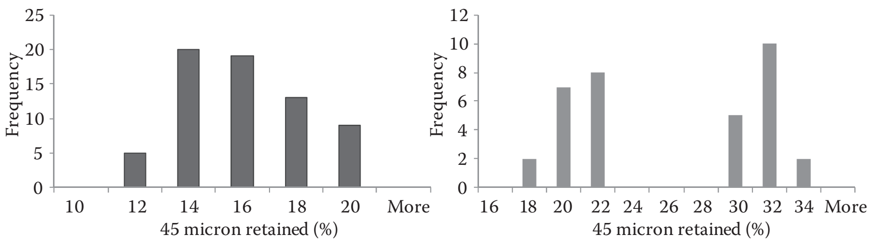
Source	Unit	Dadri	Panipat	Farrakka	Kahalgaon	Ennore	Ramagundam	Nasik	Kota	Ratnagiri
Blaine fineness	(m^2/kg)	331.1	337	325	340	400	325	385	401	NA
Compressive strength as % of cement	(%)	81	92.5	88.5	93.8	86.2	88	84.2	89.5	NA
Lime reactivity	MPa	5	6	4.8	5.8	5.2	4.8	5.6	5.84	4.8
Autoclave expansion	(%)	0.018	0.02	0.025	0.03	0.04	0.071	0.06	0.06	0.5
Specific gravity		2.21	2.3	2.1	2.27	2.2	2.09	2.26	2.25	2.39
Loss on ignition	(%)	0.67	4.66	0.8	0.11	2.54	0.1	0.8	1.23	0.84
Silica (SiO_2)	(%)	56.33	61.02	64.58	61.15	56.2	63.84	60.72	63.49	57.19
Iron oxide (Fe_2O_3)	(%)	4.09	4.47	5.27	5.57	6.8	3.85	5.32	4.33	4.8
Alumina (Al_2O_3)	(%)	33.14	23.91	25.89	26.66	25.8	25.5	27.5	26.42	25.88
$SiO_2 + Al_2O_3 + Fe_2O_3$	(%)	93.56	89.4	95.74	93.38	88.8	93.19	93.54	94.24	87.87
Calcium oxide (CaO)	(%)	1.06	1.5	0.59	1.37	3.67	1.45	1.42	2.23	1.58
Magnesium oxide (MgO)	(%)	0.95	0.72	0.26	1.31	1.76	1.22	0.48	0.81	0.75
Total sulfur (SO_3)	(%)	0.14	0.17	0.31	0.03	0.47	0.22	0.21	0.09	0.22
Alkalies ($Na_2O + K_2O$)	(%)	1.29	0.11	0.068	0.89	2.07	1.72	1.71	0.52	0.22
Chloride	(%)	0.008	0.01	0.009	0.01	0.52	0.3	0.36	0.02	0.019
Retained on 45 micron	(%)	16.7	22.5	20.2	17.1	19.6	31.9	12.4	14.34	13.7
Reactive silica oxide	(%)	38.44	NA	NA	20.54	NA	NA	NA	31.05	NA

Lack of literate effort required for treating fly ash as a usable material, improper regulation of the process of fly ash generation and handling, and lack of quality assurance (QA) and control regime when lifting/collecting fly ash lead to higher variability. The challenge then is to understand how much variation is ideally acceptable. IS 3812 [18] has uniformity requirements based on the moving average of the previous 10 samples and states that the subsequent 10 samples should be within 15% of this average for 45 μm retained and lime reactivity, whereas ASTM C618 [19] states this value to be 5% for density and fineness. The uniformity should be based more on the average value observed during lab and field trial mix design, and an attempt should be made to capture potential variations at the fly ash collection point. Uniformity and acceptance criteria need to evolve based on the response of a mix to changes in the fineness of fly ash.

Figure 15.9 shows an example of fly ashes collected from two different sources along with the statistics. Variations in fly ash-2 are large and reflected by the standard deviation, whereas a higher coefficient of variation shows higher process variation and in turn reflects relatively poorer QA. Despite the fact that fly ash acceptance sometimes becomes difficult, an appreciation of its impact on the intended application is essential, otherwise it is very easy for the employer and the contractor to hesitate using fly ash in larger volumes. Whether the reason for such apprehension is poor process control or "fly ash as a material" is a matter of engineering discretion. To elucidate on this point, refer to Figure 15.10. The dashed line indicates moving average, while the global average is 15.03%. With the moving average concept, the control lines are also moving, whereas if we take the global average, there would be a definite band within which the 45 μm retained value will have to fall.

15.3.4.2 Quality Assurance

The QA regime at the fly ash lifting/collection point, at the receiving end (incoming inspection), and during usage needs to be carefully exercised. With increasing demand for consumption of fly ash, the supplier of fly ash has to be educated enough



Fly ash source	Average	Std. dev.	Coefficient of variation
	(%)	(%)	(%)
Fly ash-1	15.03	2.34	15.57
Fly ash-2	25.0	5.7	22.75

FIGURE 15.9 Variability in fly ashes based on fineness.

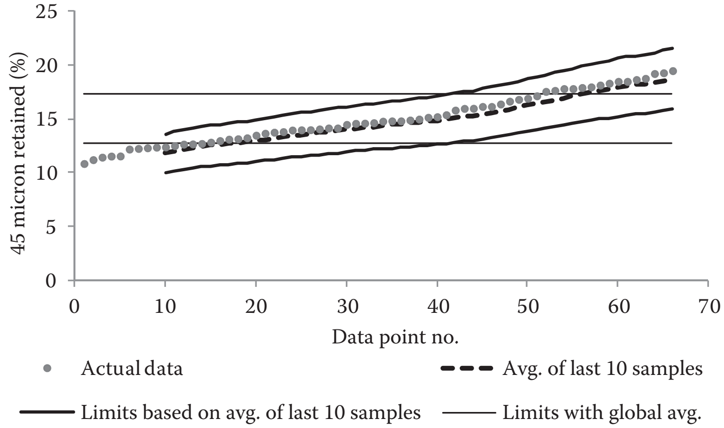


FIGURE 15.10 Uniformity requirements, effect of average calculations.

to understand the implications of his or her operations on the eventual sustainability. If transporters are allowed to lift and supply the fly ash, then it jeopardizes the QA at the source. The onus then lies on the thermal power plants and more on the contractor and/or RMC manufacturer who receives/accepts the fly ash. Another issue with installing QA at the source is the lead distance of the fly ash source from the actual construction sites. More often than not, the farther the contractor/purchaser from the fly ash source, the lesser his or her control over the quality and the lesser his or her ability to reject the fly ash based on incoming inspection. A way to mitigate this is to have a "middle man" or an authorized supplier who lifts the fly ash from its source, runs his or her QA and QC, and then supplies after conforming to the standard requirements. Albeit this increases the cost of fly ash, it dramatically enhances the comfort of the contractor and eventually the consistency and performance of the concrete.

A practical strategy followed by large projects for dedicated supply of fly ash is an initial inspection (including testing over a period of time) of thermal power plant for determination of a fixed collection point. The on-site demand for fly ash has to be balanced with the daily collection of respective electrostatic precipitator. A quality statistic is then built to regulate the collection and incoming inspection with periodic visits to the thermal power plant.

15.3.4.3 Adequacy of Mix Designs

The mix designs developed in the lab should take into account the potential variations in the fly ash and its effects on the required properties, required degree of quality control for long-term measurements of fly ash concrete properties, and annual temperature changes, among others. Practical apprehension in delayed setting and hence stripping time often limit the use of fly ash during winter. Large infrastructure projects often struggle in winter to meet similar-to-summer demands on engineering properties. Practical ways of dealing with this issue need to be adequately addressed.

Mixture proportions for winter should be adequately modified by suitably changing the mixture proportions while matching and conforming to the engineering properties.

Responsive-to-weather mixtures can certainly be tailored with advancements in the admixture technology, for example, the use of accelerators. Preheating of aggregates and water is another way of increasing the placement temperature. This, however, should be done with proper design calculations from the temperature steel point of view while balancing the pour schedules, e.g., surface area/volume ratio. Material for form can also be changed in order to improve the insulation to concrete.

For these changes to be responsively adopted, there needs to be some flexibility in overall approach to engineering and construction including specifications. Employers and contractors, while harnessing the economical benefits, often forget that at times, a portion of such benefit will have to be put back in order to be sustainable in the long term. Such responsibility should, however, be shared with an adequate engineering understanding and sustainability reward/credit system.

15.3.4.4 Classification Systems

Classified fly ash, produced using cyclone separators, is available in India to a limited extent. The classification of fly ash narrows down the particle size distribution, regulates the fineness, and ensures consistency in the quality of supplied material. In the pursuit of getting fly ash at relatively lower price by collecting and directly using in cement or concrete, the quality at times is overlooked. Some fly ash sources are more consistent than others, and each source has to be dealt with on a case-by-case basis.

15.3.4.5 Construction Precautions

Construction precautions like reinforcement detailing, pour sequence and schedule, formwork type and stripping time, pour volume and surface area, insulation, and curing period are critical if fly ash-based concrete is to be consistently used as a sustainable option. Application of calorimetric techniques and in situ temperature measurements are very useful in doing detailed planning. Sensitivity of mixtures to temperature, especially related to bleeding, slower setting and strength gain, plastic shrinkage, and formwork insulation need to be carefully studied. Knowledge regarding some of these factors exists, whereas others need to be investigated. In general, hesitation exists in applying field-based observations to full-scale structures promptly, often leading to adoption of non-fly ash concretes and/or delays in taking sustainable engineering decisions.

15.3.5 State of the Art—Codes and Contractual Specifications

15.3.5.1 Characterization of Fly Ash

Fly ashes are complex inorganic–organic mixtures with unique, polycomponent, heterogeneous, and variable composition, containing intimately associated and finely dispersed solid, liquid, and gaseous components. The composition and properties of fly ashes have been characterized in detail and summarized. Briefly, the phase and mineral compositions include

- Inorganic constituent—composed of noncrystalline (amorphous) matter, namely, different glassy particles, and crystalline (mineral) matter such as crystals, grains, and aggregates of various minerals

- Organic constituent—composed of char materials (slightly changed, semi-coked, and coked particles) and organic minerals
- Fluid constituent—composed of liquid (moisture), gas, and gas–liquid inclusions associated with both inorganic and organic matter [20]

The following points are relevant:

- The construction industry classifies fly ash into two major types depending on the calcium oxide content (and lime reactivity) as low-calcium fly ash ($50\% < SiO_2 + Al_2O3 + Fe_2O_3 < 70\%$) and high-calcium fly ash ($SiO_2 + Al_2O_3 + Fe_2O_3 < 70\%$). In reality, the pozzolanic activity depends on the quantity of reactive materials (glassy phase), the rate at which these reactive materials enter into the hydration reaction, fineness, and mineralogy. The complicated composition, fine size, and variable particle morphology and properties of fly ashes provoke serious problems with their characterization, specification, and utilization. Chemical and physical characteristics are commonly used for specification and industrial application of fly ash. However, these chemical classifications are insufficient for specification and reliable determination of applicability of fly ashes. This is because the abundance and properties of minerals and phases in fly ash have a leading role for that [20–22]. In a nutshell, if we have to move toward sustainable concretes, the codes (and in turn the specifications) need specific long-term and performance-based changes.
- The existing fly ash classification scheme is bereft of calcium oxide (CaO) content; research has indicated that there is a linear relationship between $SiO_2 + Al_2O_3 + Fe_2O_3$ and CaO. It has been pointed out that specifying either the summation of three oxides or CaO would be sufficient. Determining CaO would be beneficial for indicating certain durability parameters and has hence been proposed for inclusion in the classification scheme [23].
- Strength activity index, compressive strength, and lime reactivity tests (all at the maximum age of 28 days) are stipulated in classification schemes in the codes and specified in construction specifications. It is important to note that fly ash reactions kick in late, and 28-day indices may not be very indicative of the utility of a fly ash. The Japanese standard on fly ash stipulates activity index at 91 days in addition to 28 days [24]. In general, these indices should be stretched to 56 days at least. Furthermore, application of any or all of these indices in selecting fly ash for an application depending on the nature of the structure needs to be encouraged and brought into practice. Lime reactivity is the test to measure the reactivity of fly ash with lime produced during hydration of the cement. The Indian standard is the only one to specify the test, and research has found the test to be a better measure of fineness than reactivity, which hence may not be a useful test.
- Maintaining the uniformity in collected and hence supplied fly ash is a responsibility of the supplier, and accepting the fly ash within the agreed range of variation is a responsibility that needs to be exercised by the purchaser. Often under the pressure of construction schedule, quality is put aside.

It need not be reiterated that fly ash reactivity is critically decided by the fineness. The fineness can be measured in various ways; however, 45 μm retained is a low-cost, reproducible, and effective way for measuring, monitoring, and being used as acceptance criteria during incoming inspection. For measuring uniformity of the fly ash, a test or index of variance on retention on 45 μm should be quite useful, as specified for silica fume.

15.3.5.2 Prescriptive Specifications

In a recent research report [23] investigating the potential improvements to specifications and test protocols to determine the acceptability of fly ash for use in highway concrete, researchers recommended the need for improvements in tests and specifications to better identify those properties affecting the concrete performance. Areas identified for improvement include better characterization of

- The strength development associated with the use of fly ash
- The carbon fraction of fly ash and its influences on air entrainment
- The level of cement substitution with a specific fly ash to mitigate alkali–silica reactivity

It is also commented that the improved specifications would generally require a new classification approach that better characterizes coal fly ash performance in concrete mixtures. The purpose of classification is to group fly ashes that are similar without excessive testing. The purpose of characterization is to measure and report properties that are known to affect performance, and those properties serve as a basis for the classification system. Therefore, the method used for fly ash characterization may not necessarily be appropriate for use as a classification method.

15.3.5.3 Quantity of Fly Ash

Table 5 in IS 456 [25] limits the use of fly ash to 35%, although there is no limit on the quantity of fly ash to be used in the mix. This clause of 35% limits the cement replacement levels also to 35%, and recalculated minimum cement contents considering this limit are shown in Table 15.4. This limit of 35% has no scientific basis. Research focused on performance and durability is required for arriving at optimal cement replacement levels for Indian fly ashes and cements.

IS 456 allows the use of fly ash of more than 35% as a replacement of sand or as mineral admixtures. The only difference is that those as mineral admixture or replacement of sand will not be counted as cementitious materials when calculating the same for conforming durability clause. It also needs to be noted that the table in IS 456 is irrespective of the grade of cement, the consideration for which would definitely impact these limits. Another fact worth juxtaposing is the characterizing age of concrete. Even if the characteristic strength is measured at 28 days, with the advent of latest PC-based admixtures, this table needs to be revisited.

15.3.5.4 Use of HVFC and High-Performance HVFC

It has been over three decades since HVFC and high-performance HVFC were initially researched [26,27]; many field trials have also been performed, and yet this

TABLE 15.4
Allowable Replaceable Cement Quantities as per IS 456 and HVFC Considerations

	PCC				RCC			
Exposure Class	Min. Grade	Min. Cement Content (kg/m^3)	Min. Cement with 35% Fly Ash (kg/m^3)	Corresponding Binder Content for HVFC[a] (kg/m^3)	Min. Grade	Min. Cement Content (kg/m^3)	Min. Cement with 35% Fly Ash (kg/m^3)	Corresponding Binder Content for HVFC[a] (kg/m^3)
Mild	–	220	143	286	M20	300	195	390
Moderate	M15	240	156	312	M25	300	195	390
Severe	M20	250	163	325	M30	320	208	416
Very severe	M20	260	169	338	M35	340	221	442
Extreme	M25	280	182	364	M40	360	234	468

[a] Calculated considering minimum cement required. For example for severe exposure, the minimum cement content is 320 kg/m^3. With 35% fly ash, minimum cement content comes to 208 kg/m^3. For producing HVFC, an equal amount of fly ash is required, hence binder content is $2 \times 208 = 416$ kg/m^3.

sustainable concept has not come into mainstream construction. RCC dams are certainly an exception. The reasons could be manifold. With regard to the IS code, the provisions need a careful review. Table 15.4 shows the computed binder contents for making HVFC while limiting maximum cement replacement to 35% of the minimum cement content. The limit on the cement replacement might as well be limiting the durability of concrete. The binder content that emerges appears to be on a higher side and could be optimized subject to relaxations on the specified limits for the minimum cement content. Studies have indicated that such prescriptive limits on fly ash amounts do not help concrete performance in any way and may actually limit the improvement in concrete durability [28].

15.3.5.5 Specifications

Material specifications used in most construction contracts refer to respective Indian standards or international equivalents. This is done with inadequate consideration for the type of structure being constructed. This, in turn, limits the use of higher volumes of fly ash in concrete. In India, there is certainly good scope in

- Evaluating the fly ashes, including pond ashes for their performances in concrete and furthermore characterizing concrete's performance in turn
- Reviewing of structure-based optimization of fly ash in concretes specifically in terms of the requirement of the respective properties

For example, during summer, the use of fly ash can be increased, and in winter, it could be lowered. For mass concretes, fly ash could be used up to 70% with longer characterizing ages. Fly ash could be optimized in pavements depending on the surface area/volume ratio, shrinkage, and abrasion resistance.

15.3.6 Way Forward

The biggest challenge in brining sustainability into practice and not retaining it as another engineering jargon is the willingness to change and accept change. An appreciation of what is really required is essential—do we want to construct for ourselves, leaving nothing for the coming generations, or do we perform some responsible construction? Today, we may have the power to spend, but that also brings responsibility to spend sensibly.

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