M. Boştenaru Dan
R. Přikryl · Á. Török
(Eds.)



Materials, Technologies and Practice in Historic Heritage Structures

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Cover illustrations: Left: reinforced concrete column at the church of the Holy Spirit in Ottakring (1910–1912), Vienna, Austria, by the Slovene architect Joze Plecnik in Vienna, Austria. Middle: adobe bricks at a house in Kiskunfélegyháza, Hungary. Right: pavement of round river stone typical for the centre of Pavia, Italy. Photographs taken by Maria Bostenaru Dan, 2006.

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Preface

This book aims to strengthen the knowledge base dealing with materials in historic structures, their properties, technology of use and conservation, and their performance in transforming the environment. Many of the papers in this volume were presented during the European Geosciences Union General Assembly (sessions: GMPV10 “Challenges to historical materials in urban/anthropic environments”, and ERE10 “Natural stone resources for historical monuments”) held in Vienna, Austria (2006, 2007 and 2008). In addition to these a number of invited contributions have been chosen to fill gaps in the coverage of the meetings’ original aims.

The book consists of 17 chapters dealing with inorganic construction materials used in historic structures such as adobe, stone, brick, binders, concrete and plasters. The aims of the editors were to select contributions describing various materials and not to restrict the book to one specific historic material. The idea behind this approach was that at most historic sites a great variety of materials are used; and so a variety of approaches are needed to understand the present state and future changes in the materials. The authors are leading experts from various backgrounds in the fields of architecture, civil engineering, geology, materials and conservation science. This multi-disciplinary approach allowed for the coverage of historic materials from various aspects.

The Part I of the book deals with earth as the most ubiquitous and versatile building material. One paper focuses on a UNESCO World Heritage Site in earthen architecture built by the Arabs: the Alhambra in Granada, Spain. The other two papers focus on brick; and a description is given of its manufacturing processes and properties. A case study from a World Heritage Site in Vietnam draws attention to the wide-range of uses of this historic material.

The Part II deals with natural stone. Natural stone was a particularly important construction material used for numerous locally and globally well-known monuments. The papers on this historical construction material cover a wide geographical range throughout Europe and provide examples of various techniques used in diagnostic studies.

The Part III covers binders, concrete and the combination of different techniques; it provides some of the innovative aspects of the book: the view on the evolution of the binder based materials from Roman times till the present; opus craetecicum and the combination of this technique with brick and stone; pre-Portland cement mortars like pozzolanic and lime mortars; Roman cement; and finally early reinforced concrete.

The closing group of papers deals with the engineering approach needed to monitor and reduce the seismic hazards for historic structures and masonry buildings using innovative techniques such as that of Fibre Reinforced Polymers (FRP).

We would first like to thank the authors who participated in this publication project. Without their high quality contributions and patience during the long preparation process the book would have not been possible. The gathering of this book together could not have been done without the help of numerous colleagues who kindly agreed to review the manuscripts submitted. Their work against the clock improved the level of the papers considerably. The following persons were involved in the review process: Donato Attanasio, Luigia Binda, Karel Drozd, Gianmarco di Felice, Dionys Van Gemert, Jungner Högne, John Hughes, Nicoletta Marinoni, Laura Russo, Massimo Setti, Antonio Santos Silva, Luigi Sorrentino, Marios Soutsos, Fernando Veniale, Maureen Young, Konrad Zehnder. The review process and editorial handling were financially assisted by the institutional research project of the Ministry of Education, Youth and Sports of the Czech Republic: MSM 0021620855 “Material flow mechanisms in the upper spheres of the Earth”; and they also benefited from the support of the Hungarian Scientific Research Fund (OTKA, grant no. K63399), and the Marie Curie Reintegration Grant (European Commission, contract MERG-CT-2007-200636 with Foundation ERGOROM ’99, Bucharest). The organisation of the session GPMV10 and the work towards the publication agreement of the first editor were funded by the MEIF-CT-2005-009765 Marie Curie Intra-European Fellowship at the Istituto Universitario di Studi Superiori di Pavia, Italy (European Commission).

Finally, we would like to particularly acknowledge help from the Springer staff during production of this volume, especially publishing editor Petra van Steenbergen, whose comments and suggestions have significantly contributed to the finalization of this book. We also thank Cynthia de Jonge for her kind help.

Bucharest	Maria Bostenaru Dan
Prague	Richard Přikryl
Budapest	Ákos Török
March 2009	

About the Editors

Diplom-Ingenieur **Maria Bostenaru Dan** obtained an engineering degree in architecture, with specialisation in urban planning, in 1999 from the Universität Karlsruhe (TH), Germany. She was involved, within the Collaborative Research Centre SFB (Deutsche Forschungsgemeinschaft funding) 315 “Preservation of historically relevant constructions”, in a building survey in Poland, and was employed as part time research assistant in the SFB 461 “Strong earthquakes: from geosciences to civil engineering” both at the Universität Karlsruhe. She also started as a student research on sociology of architecture, namely the participative approach, which resulted later in one of her books. She was also employed as part time research assistant on a Universität Karlsruhe internal project on marketing for the university, called Uni-Mobil and on a soil-moisture project. She did research as guest student at the State School for Arts and Design in Karlsruhe on “Spaces of Encounter” with the topic “The Rediscovered Space”. With a three year Deutsche Forschungsgemeinschaft (German Research Foundation) scholarship in frame of the Research Training Group “Natural Disasters” in Karlsruhe and a six months Marie Curie Early Stage Research Fellowship (European Commission funding) in Pavia, Italy, research was done on “Applicability and economic efficiency of seismic retrofit measures on existing buildings” and student individal studies and diploma works supervised. She was experienced researcher on the two years project “Preservation of historic reinforced concrete housing buildings across Europe” (CA’REDIVIVUS), a Marie Curie Intra-European Fellowship (European Commission funding) in Pavia. She returned to her home country, Romania, with a three year Marie Curie Reintegration Grant (European Commission funding) for research on “The innovation in the plan of the current floor: Zoning in blocks of flats for the middle class in the first half of the 20th century” (PIANO) at Foundation ERGOROM ’99. Since February 2008 she is also employed at the “Ion Mincu” University of Architecture and Urbanism, Chair for Conservation and Restoration, as researcher, a permanent position, collaborating also with the Research Centre of the University for Architectural and Urban Studies, where she edits a book on "Urban Regeneration in the Framework of Romanian Cities Transformation. Present State and Development Trends" in a collaboration framework with the University of Genova, Italy. There she was involved in a Consiliul Național al Cercetării Ştiințifice din Învățământul Superior (The National University Research Council, Romania) funded research on "Arts, Urban Communities, Mobilisation - The social reinsertion of the artistic and architectural project", in putting in value the Tzigara-Samurcaş historical glass slides photographs archive, a project co-funded by the Romanian Union of Architects, and in the documentation for the edited book on research at the department. She keeps contact with earthquake engineering through a P4 of the Planul Național de Cercetare, Dezvoltare şi Inovare II, Autoritatea Naționala pentru Cercetare Stiințifică (the Romanian 2007–2013 research framework) project lead by the University of Bucharest, the Centre for Risk Studies, Spatial and Dynamic Modelling of Earth and Coastal Systems: "Multihazard and Vulnerability in the seismic context of the city of Bucharest" (HERA) and through the voluntary project "World Housing Encyclopedia", run by the EERI from Oakland, California, USA, and the IAEE, where she is participant since 2001. With the HERA project research she participates in the European Network COST Action TU0801 "Semantic enrichment of 3D city models for sustainable urban development" (European Science Foundation funding), as management committee member. She has been recently invited to collaborate with the University Centre for Emergency Architecture and Urbanism ("Ion Mincu" University), and since October 2009 is associated teaching staff at the Department for Urbanism, co-teaching a course on (natural and anthropic) "Risks" for Master (Bologna) in "Urban Design" with Cristina Olga Gociman, director of the Centre and course titulaire.

She has been active member of a number of professional associations, responsibilities including being member of the advisory board (Marie Curie Fellows Association, 2003), editorial board member (2003–2006) for the "World Housing Encyclopedia", which published a summary in 2004, journal guest editor for "Natural Hazards", "Bulletin of Earthquake Engineering", "Natural Hazards and Earth System Sciences" and "International Journal of Architectural Heritage", reviewer for the EuroScience Open Forum 2004, the 13th World Conference on Earthquake Engineering and the journals "Natural Hazards and Earth System Sciences", "Building and Environment", "Risk Analysis", and "International Journal of Architectural Heritage", organising and chairing conference sessions in the framework of the European Geosciences Union and the former European Geophysical Society from 2002 on. She published two books, both in German, entitled "Applicability and Economic Efficiency of Seismic Retrofit Measures on Existing Buildings" (2006) and "From the participation models of the 70s to communication forms at the end of the 20th century in architecture and urban planning" (2007), and more than 90 scientific contributions.

Richard Přikryl graduated in the field of geology of mineral deposits and geochemistry at Charles University in Prague, Czech Republic in 1992. During doctoral studies (Ph.D. thesis defended in 1998), he focused on the influence of rock fabric on the physical and mechanical properties of common building stones (granites). In 1996, after obtaining a scholarship from Swedish government, he was involved as a research fellow for a project studying effects of indentation on rock fragmentation at the Luleå University of Technology, Sweden. Since 1994, Richard Přikryl is employed at the Faculty of Science, Charles University in Prague, first as a lecturer, from 2002 as associate professor. During 2001–2005, he was commissioned to be director of the Institute of Geochemistry, Mineralogy and Mineral Resources of his home University. From 2005, he is a head of the School of Doctoral Studies of Applied Geology. Along with extensive teaching activity in the field of natural resources (Introduction to the Study of Natural Resources; Geology of Mineral Deposits; Geology and Technology of Non-Metallics; Geology of Building Raw Materials; Prospecting, Exploration and Evaluation of Natural Resources; Technical Petrography), he is deeply focused in the research of natural stone (experimental testing, provenance studies, durability evaluation, etc.). During past 15 years, he was principal investigator of 11 national and 3 international scientific research projects and of 21 contract works including applied research like mapping of the Charles Bridge masonry, evaluation of natural stone deposits suitable for the repair of historical monuments. Since 1998, he is active in the informal international network of scientists interested in the study of natural stone and its weathering processes (Stone and Atmospheric Pollution NETwork). Richard Přikryl was main organizer of 3 international conferences (2001 – Stone and Atmospheric Pollution NETwork, 2002 – Lux et Lapis, 2004 – Dimension Stone). In the frame of annual EGU (European Geosciences Union) meetings, he organized 6 sessions focused on natural stone and aggregates during 2005–2008. Based on these activities, he was main editor of 4 books published by Taylor and Francis, Geological Society London and The Karolinum Press. He co-operates and publishes with several research groups including the one headed by Prof. Ákos Török (Department of Construction Materials and Engineering Geology, Budapest University of Technology and Economics), Prof. Bernie Smith (Queen's University Belfast) and Prof. Karel Miskovsky (Luleå University of Technology).

Ákos Török (1963) is a habilitated Associate Professor at the Budapest University of Technology and Economics and the head of Engineering Geology Division at the Department of Construction Materials and Engineering Geology. He is a graduate geologist (Eötvös Loránd University) and he also received a M.Sc. degree in environmental engineering (International Technological University, UNESCO) and a PhD degree in geology (Eötvös Loránd University). At the beginning of his career he was mostly interested in sedimentology and he was a scholar at the Geological Survey of Denmark in Copenhagen and at Postgraduate Research Institute for Sedimentology, Reading University (UK). In the early 1990s he has started to work in the field of engineering geology and rock mechanics. His main field of research includes material testing under various conditions, diagnostics of monuments, air pollution related changes in stones, weathering simulations. At the Engineering Geology Division he is currently the coordinator of engineering- and hydrogeological expert panels of major construction projects such as the new metro line in Budapest and the radioactive waste disposal site in S-Hungary.

From the late 1990s he has also started to work in conservation science and in 2005 he received a library research grant from Getty Research Institute, Los Angeles in this field. Dr. Török was a principal investigator in several international research programmes with China, Czech Republic, France, Germany, Greece, Portugal, Spain, and UK on monumental stone decay, conservation science, fire-related changes in construction materials, slope stability analyses and urban geological hazards. He has been an active committee member of COST action on "Built Heritage: Fire Loss to Historic Buildings" (C17) and he is currently a management committee member of action "Urban Habitat Constructions Under Catastrophic Events" (C26).

His teaching experience of more than 20 years involves courses at graduate, postgraduate and Ph.D. levels in various fields of geology and conservation science. As an invitee he has given courses and lectures at University of Malta, Charles University of Prague (Czech Republic), Göttingen University (Germany). Under the auspice of his supervision Ph.D. graduates have been working on slope stability, engineering geological analyses of radioactive waste disposal site, hydrogeology, stone conservation as well as laboratory and in situ testing of natural and artificial stones.

He has published more than 120 papers including book chapters and papers in referred international journals, conference proceedings and Hungarian periodicals. He is the author of the textbook Geology for Engineers (in Hungarian) and the editor of several publications. He is the president of the Hungarian National Group of the International Society for Rock Mechanics (ISRM) and also the Hungarian National Group of the International Association for Engineering Geology and the Environment (IAEG). In 2008 he was elected as a member of Permanent Scientific Committee for the organization of International Congresses on Deterioration and Conservation of Stone. At national level he is the acting president of the Engineering and Environmental Geological Section of the Hungarian Geological Society and an elected member of the Geological Committee of the Hungarian Academy of Sciences. His research activity was rewarded by Bolyai Medal of the Hungarian Academy of Sciences in 2008.

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Contents

Part I
Adobe and Bricks

Chapter 1
Introduction

Maria Bostenaru Dan

1.1 Novelty of the Book

Planners cannot set out today from a *tabula rasa* situation anymore. Environmental and sustainability issues have already formed public opinion firmly about a 'green-belt' being necessary in our cities, a kind of fortification leading to intensive development in towns inside a clearly delimited area within the surrounding nature. Since building on the periphery is limited, and the existing built substance has a certain cultural, architectural or at least environmental value, upgrading of existing buildings gains more and more ground from the design of new buildings.

Masonry has already long been recognised as the construction material par excellence for historic structures. Reinforced concrete has not yet been so recognised. The reason for this may lie in the fact that concrete has not been employed for very long: thus buildings having a concrete structure are generally regarded as 'not old enough' to be considered historical. But the International Council on Monuments and Sites, at a joined seminar with UNESCO and the International Centre for the Study of the Preservation and Restoration of Cultural Property in 1995 in Helsinki, considered the systematic documentation of the 20th century heritage, when these buildings were erected. The book includes chapters on these components of the building stock which have not been covered by previous studies, although they have architectural or cultural value. Special attention was given to a recommendation of the ICOMOS seminar in Helsinki, which sets out to encourage research pro-

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grammes on specific problems concerning techniques and materials in restoration work, to take into consideration their aesthetic qualities. Some ICOMOS members are authors of chapters in the book.

1.2 Background

The motivation for the session "Challenges to historical materials in an urban/anthropic environment" was that materials and technology constitute the physical basis of preservation issues. Regardless of common or heritage protected buildings, mineral materials play a role in urban sustainability. This session investigated the challenges relating to historical materials in conservation projects in urban environment. The call for contributions to the session was related, but not only, to:

- construction materials, properties, craftsmanship, labour, know-how;
- changes in the use of materials induced by technological and industrial development;
- weathering;
- natural disasters;
- historic mortars;
- sustainability of street facades;
- preservation issues;
- investigation methods with minimum intervention;
- effects and incompatibilities on the existing materials of interventions made with new materials.

The objective of the book based on that session is to put together critical investigations of the relationship between the formal discourse of the employment of materials in heritage structures and the technological developments that (trans)formed it.

A topic like the subject of this session is rather rare, as most frequently mineralogical approaches to the human built or modelled environment approach archaeological research. Nevertheless, a similar session was held in the framework of the Annual Meeting of the German Mineralogical Society in 2004 in Karlsruhe, Germany, building on the research tradition of the Collaborative Research Centre (SFB) 315 "Preservation of Constructions of Historic Importance", funded by the German Research Foundation at the University of Karlsruhe (TH). No full publication of the constituent papers followed that special session.

In German the term *Baukonstruktion* is used in order to name a discipline which deals with the construction of buildings and construction works. The subjects of the discipline are the building elements as well as the joining of building elements, in other words, construction technology. The science of construction materials is a discipline adjacent to it.

In 2006 the session “Challenges to historical materials in urban/anthropic environment” was organised within the European Geosciences Union General Assembly framework of the Marie Curie Intra-European Fellowship project “Preservation of historic reinforced concrete housing buildings across Europe” funded from the European Commission and the publication of the book was planned following this to cover the gap. In 2006, 2007 and 2008 the co-editors of the book organised a session series on “Natural Stone Resources for Monuments” in the same framework of the European Geosciences Union General Assembly.

Consistently with the approach followed, an invitation was issued to experts in the field of earthquake engineering who were involved in both practical and research activities concerning historic built spaces in long-term and short-term earthquake protection.

The studies focussed on the histories of the building industry, materials, know-how, labour and craftsmanship as these have (trans)formed the theory, practice and conservation of architecture both over time and across different geographical contexts. In terms of preservation, issues related to technology, practice and materials continue to form the basis of the physical problem in conservation projects.

1.3 Organisation of the Book

The book is organised in four parts: the first three concern mineral building materials and the fourth is a synthesis on the effects of natural disasters, in particular earthquake risk. There is a paper on adobe/earth material, and two each on bricks and on seismic risk, although other parts also include papers relating to seismic risk, namely a mixed materials chapter in the section on binders, concrete and mixed materials. There are six chapters each in the parts relating to natural stone and the part dealing with binders, concrete and mixed materials.

The first section is on earth material, unburned and burned alike. The paper dealing with rammed earth material deals with the conservation of a rammed earth construction built by the Arabs. It is about the conservation of the Alhambra palace in Granada, Spain, and it concerns resistance to water in particular. Constructions out of this material need urgent studies concerning their conservation; and although architectural history studies are frequent, studies on conservation of materials are rare, the earth material being considered a “poor” construction material. This site belongs to the World Heritage List. In this section there are two chapters on bricks, one dealing with the manufacture and properties of ancient bricks in Europe, and case study heritage structures and churches from the 12^{th} and 18^{th} centuries in Portugal. The other chapter deals with religious architecture as well: the Hindu temples of Mỹ Sơn in Vietnam, also on the World Heritage List. Apart from the description of building materials, the construction techniques of the Cham people are investigated including how these techniques have influenced structural behaviour.

The chapters on natural stone deal with marble, sandstone and limestone in some European cities, although a remarkable heritage in natural stone is to be found also in the World Heritage Site of Quebec City, in Canada; thus the studies in this section have universal value. There are chapters dealing with sites from Roman antiquity, the Middle Ages, the Baroque period and a synthesis paper on the history of the city of Dresden mirrored by its building stones, focusing on modern times. In cities with tradition of building in stone this was used also in modernity: in the Art Nouveau or limestone functionalism in Tallinn, Estonia, or bringing traditional elements in Modernism in Balchik, Bulgaria. Building stone is presented as a means of research into the history of architecture as it can both lead to establishing through the provenance of stones of the existing commercial links at the time of the construction and also it can be a mirror of regional influences up to today, in the age of globalisation. Another two chapters deal with deterioration and conservation issues, building on the same common denominator that the history of building stones can help the historical study of architecture since deterioration and conservation are to be seen in a complex relationship of history, environment and stone character. Geographically the case studies are from South Italy and Poland but with comparisons throughout Europe, Scotland, Ireland and Eastern Germany. Finally the last two papers deal with concrete conservation approaches, such as how to establish the quarries where natural building stone can be obtained today for conservation measures and in situ non-destructive testing measures respectively.

The section on binders, concrete and mixed techniques includes some chapters which add extra value to this book, namely the ones dealing with concrete from Roman antiquity to the present day. In the case of mortars the chapters deal with mortars before the introduction of Portland cement, namely pozzolanic mortars, lime mortars and Roman cement. Pozzolanic mortars are exemplified by Portugal, particularly the volcanic islands, in a geographic overview from Roman times to the present. Their compatibility with new mortars is investigated. Another chapter deals precisely with this, the design of mortars for conservation interventions. The third chapter on historic mortars describes a European project on the Roman cements, the material of the 19th century and how they should be conserved and even manufactured afresh. Historic mortars are not only a construction material to be conserved or to be used in conservation, but are also useful for the history of architecture, as was shown for history of architecture in the case of natural stone. Historic mortars, which indicate the age of the construction, are a tool for age determination.

Regarding concrete, the first paper deals with *opus caementicium*, and how this made possible the technique of vaults in the Roman empire in the Basilica of Maxentius, to which an extensive study is dedicated, including also the “industrial” production of bricks during the Roman empire, the mortars, the stuccos and the marbles. The Basilica was also damaged by an earthquake, shortly after its construction. The chapter on the use of historic concrete in the age of modernity, at the beginning of the 20th century, also deals geographically with Italy. These early works in reinforced concrete have been neglected in studies of monuments and here the book fills an important gap. The focus is on assessing the structural capacities and leads up to conservation issues of early concrete, which was at an experimental stage when the buildings were constructed.

The fifth section deals with stone masonry constructions subjected to earthquakes. The first one concerns the conservation of masonry constructions through seismic retrofit, analytically and experimentally investigated, with various techniques—the accent being on the innovative technique of fibre reinforced polymers. Also here the book covers an important gap in the existing literature. The masonry buildings of Slovenia are mainly made out of stone, but sometimes also brick. The chapter builds in its definition of "heritage" on the Declaration and the Charter of Amsterdam (1975) which considers as cultural heritage groups of buildings of lesser value belonging to the centres of European cities. Finally the last chapter deals with the monitoring of the fracture damage in the cathedral of Palma de Mallorca (Spain) after the 1851 earthquake, in order to help future conservation work.

1.4 Materials

Unlike stone, brick is manufactured. In regions poor in natural stone resources, or where working the natural stone proved difficult, ceramics started to be produced. The industry of this material has at its basis a certain kind of earth, out of which through a burning process ceramic material can be obtained. It has a higher resistance than sun-dried loam. Natural stone or brick work together with mortar can be used to build structural masonry. Ceramic materials have been widely used by various civilisations, such as Assyrian-Chaldean, Persian, Greek, Roman, Chinese, in some parts of India and central Asia, and in Europe in medieval architecture or after the industrial revolution. The use of brick for construction was not limited solely to regions that lacked stone or other materials suitable for building close at hand: bricks were often used, even in areas where stone was available, for reasons including speed of construction and economy. Manfred Hegger's construction materials manual classifies brick under ceramic materials (Hegger 2006, pp. 48–53). The name of the material comes from the Greek keramos, meaning fired earth (Hegger 2006, p. 48).

Binders are a series of materials of very different natures but with the common property of being able to go over—in given conditions and specifically for each of them—from a fluid, liquid or plastic state into a viscous or solid state, and being thus able to bind with other various materials. Binders are used in the manufacture of binding mortars or plastering mortars, of concretes and of artificial stones cast at low temperatures. Mortars generally consist of a binding material, water and sand, sometimes with various add-ons. There are two classes of mortars: masonry mortars and plasters. Masonry mortars are used for binding masonry blocks, brick or stone, for example. Concretes generally consist of a binder, water, sand and stone aggregate. So concretes are a kind of artificial stone as well. The binder used is usually cement. Reinforced concrete is a material in which concrete cooperates with reinforcement bars or fibres. Historically iron/steel reinforcement was used, whereas the term iron-concrete was used for slightly reinforced concrete only, as opposed to steel-concrete for the more heavily reinforced type. Manfred Hegger's construction materials manual classifies concrete as "Building material with mineral binders"

(Hegger 2006, pp. 54–61). Hegger acknowledges the use over thousands of years of building materials with mineral binders. The gyps and mortar lime used by the Phoenicians, Egyptians, Trojans and Greeks has been refined by the Romans to *opus caementicium*, used most exemplarily in the Pantheon in Rome (Hegger 2006, p. 54). Concrete as such appeared in the 18th century (Hegger 2006, p. 54) when the French engineer Bernard Forest used the term *béton*. One of the first architects to display the possibilities of the material concrete was Auguste Perret, renowned for both his housing and industrial buildings erected using concrete technology. To model out of the material is consistent with the technical process of fabrication (Hilberseimer, 1928, p. 17). Mouldability of concrete was demonstrated in the works of expressionist architects like Frank Lloyd Wright (Hegger 2006, p. 54).

1.5 Historic Heritage

We came across a definition of historic heritage in the Resource Management Amendment Act 2003 of New Zealand. In this document "historic heritage" is used as a term instead of built, cultural, and natural heritage, which frequently overlap. In this definition historic heritage includes "natural and physical resources that contribute to an understanding and appreciation" of history and culture deriving from archaeological, architectural, cultural, historic, scientific or technological value. It includes historic sites, structures, places, areas, archaeological sites, surroundings associated with natural and physical resources. In this book we focus on historic structures.

1.5.1 On Cultural Value

Culture means the totality of material and spiritual values created by human kind and of the institutions necessary for the communication of these values (DEX, *Explanatory Dictionary of Romanian Language,* 2008). In the case of the built heritage, cultural value is the totality of values attributable to a building. According to Nistor (2008) the first values to be recognised were the cognitive and educative value, implying also the aesthetic and economic value, which came during the French Revolution.

A seminal work about the cultural value of buildings was written 1903 by Alois Riegl. Riegl (1999) identifies the various values of the built heritage which makes it a monument:

- memorial values
  - age value
  - historic value
  - intentional memorial value

- contemporaneity value
  - use value
  - artistic value
    - novelty value
    - relative art value

1.5.2 On Resources

Crişan (2004) observes that buildings are not just material resources, but also cultural resources. In fact, the discourse on resource architecture is a contemporary one.

The topic of the XXIst World Congress of the International Union of Architects which took place in 2002 in Berlin had as its main theme "Resource Architecture".

The topic was in concordance with the growing importance of 'sustainable development', a constant priority topic in the Framework Programmes of the European Union. In FP5 "The city of tomorrow and its cultural heritage" was a priority approach, and since then 'sustainable development' had been more and more concerned with the environment. It also includes protection from disasters, which we have addressed in our book taking as an example earthquake protection.

The built environment belongs to both architecture and urban planning, at the junction between the single building and the city. The "resource architecture" stays at the junction between the natural and the built environment.

> The building process has used the natural environment as a resource, while the built object is a resource in itself. "Resource architecture" shapes and is shaped by the ecologic, social and cultural side of our lives. Architecture takes place in a context, in a dialogue between civilisations and cultures, but also disciplines, as debated at the congress. A dialogue of civilisations concerns the techniques, of cultures and traditions, but the materials used in the process of building concern how innovations can build on traditions. Local materials are a material resource and regional identity a spiritual resource. Genius loci can involve how to build in the context of history and tradition, planning and building to protect material resources and to increase spiritual resources. (Bostenaru, 2009)

According to Crişan (2004) any architectural product includes cultural value elements; and even architecture works that are not protected legally possess characteristics which deserve to be conserved from the point of view of associated cultural values if they belong to a historico-architectural heritage. Connected to the older Romanian classification (today there is a classification of monuments of national importance and of local importance) Crişan (2004) identifies the value categories associated with different degrees of protection:

- outstanding cultural value: potential monuments, conditioned by the authenticity of the resource;
- architectural value: conditioned by cultural identity;
- environmental value: the resource contributes to the cultural quality and significance of a historic urban context, the cultural identity is on an urban scale;
- minor cultural value: the cultural significance of any architectural product.

In Bostenaru (2009) interdependence between the evolution of the concept of cultural value as reflected in cultural heritage policy documents and the categories mentioned above is seen. At first only the first category was considered (ex. in Carta di Atene, 1931) involving the environmental value of a building in a group of buildings of outstanding value as a whole. The Venice Charter (1964) expanded the concept of historic monument to more modest works of art which have acquired cultural value. In 1975 with "integrated conservation" (European Charter of the Architectural Heritage and the Declaration of Amsterdam) the scale changed from the single building to the urban or regional scale, to groups of buildings and interesting sites. Even if none of the buildings in a group has outstanding merit, the group as a whole can have. They also call for participation. The Nara Document of Authenticity (1994) expands the role of those concerned. Only the culture which developed a certain heritage can decide over its conservation, this being a form of participation. The Nara Document on Authenticity differentiates the groups of people, being experts, affected people or local authorities dealing with the object which is part of the cultural heritage. Authenticity can be material authenticity, concept authenticity, execution authenticity or location authenticity (Nistor, 2008).

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Chapter 2
Technology of Rammed-Earth Constructions ("Tapial") in Andalusia (Spain): Their Restoration and Conservation

Eduardo Sebastián and Giuseppe Cultrone

2.1 Introduction

We should begin our study of this type of construction by analysing the various definitions of *tapial*. Some authors have used the term *tapial* to describe almost all large-scale primitive constructions with earth, whilst others associate the expression with the use of earth as a building material, and consider it similar to adobe (Sánchez Hernández et al. 2000).

Originally, however, *tapial* was the mould or formwork used in the building of *tapias* or walls, so it would seem wrong to use the term to define a building material (Algorri García and Vázquez Espi 1991).

2.1.1 Previous Research into Rammed-Earth Constructions

In Spain research into ancient and historical buildings made out of earth is still in an initial phase. There has been a long tradition of research into historical, artistic, and documentary aspects of this type of construction (Torres Balbás 1981); but until recently there has been no scientific or technical research with regard to the conservation and restoration of the cultural heritage constructed with this material (de la Torre López et al. 1991; Ontiveros Ortega 1995; Parra Saldivar and Batty 2006; Hall 2007).

In Spain and in Andalusia in particular there is still a wealth of important historical buildings that were constructed out of earth (Cañas Guerrero et al. 2005;

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Jiménez Delgado and Cañas Guerrero 2006). Large sums must be spent on the conservation and maintenance of these buildings and prior scientific characterization studies are also required.

2.1.2 Historical and Artistic Importance

The Alhambra of Granada (Andalusia, Spain) is perhaps the best-known and most striking example of rammed-earth construction (Fig. 2.1), but it is obviously not the only one. There are magnificent rammed-earth constructions in different parts of America, Africa, and Asia (The Great Wall of China is an excellent example). There are also more recent, smaller-scale buildings in different parts of Spain (in Aragon and Castile for example), with perhaps the best examples being found in Andalusia (and especially in Granada which has an important architectural tradition in rammed-earth construction) where a large number of historical buildings made out of earth survive today. From the 11th century onwards earth was used very frequently in the construction of forts, city walls, and towers. This technique was also used in churches built after the conquest of the city by the Christians in 1492. The Church of San Juan de los Reyes in the Albaicín quarter of Granada, thought to be the first Christian church built in the city, is an excellent example. This year the European Community awarded a prize for the restoration work done on this building.

2.1.3 Practical Use in Building

As indicated above, the term rammed-earth refers to a building technique in which the precise materials used may vary (Bazzana and Guichard 1987). These walls were built by placing a fluid mass (in layers known as “tongadas” about 10–15 cm thick) into a formwork structure made up of two parallel boards joined together by wooden pins known as *mechinales*. The mass was then trodden down. The dimensions of the boards, or “tapiales” (about 3 m wide and 0.90 m high and varying thickness) ensured that these frames were light, manoeuvrable and easy to use (Cuchí i Burgos 1996).

The composition of the materials placed in the formwork varied greatly and is normally classified into three groups “*earth tapial*”, “*stone tapial*”, “*lime tapial*”. In most cases it was a mixture of lutitic materials and sand, with a varying amount of thick aggregate. The mass contained clay which acted as a binder, but in other cases the mass was held together with lime, especially in Spanish Muslim buildings (Valverde Espinosa et al. 1997; Sebastián Pardo et al. 2000).

The outer surfaces of the walls are not very resistant and erode easily if not protected with some sort of surface coating. This coating has other functions such as hiding any imperfections, protecting the structure from bangs or scratches, improv-

Fig. 2.1 General view of rammed-earth construction in the Alhambra (Spain)

ing the heat insulation, and enhancing the appearance of the building by providing a uniform colour (de la Torre López 1995).

A number of different techniques were used in the rammed-earth buildings built by the Arabs. In some extreme cases, the fine fraction (clay and silt) was discarded and a mixture of lime with sand and thick aggregate was used, creating a form of lime concrete, which when pressed down, became extremely hard and resistant. This was normally used for the foundations of large defensive buildings (Alcazaba Cadima of Granada, from the 11th century or the Alcazaba of the Alhambra). The other types used were:

A) The *Tapia Real* which itself appears in two forms: (1) the first is based on a series of layers or "*tongadas*" about 2–5 cm thick of 100% lime (fat lime) and other layers of earth to which lime has not been added (Puerta de las Pesas in the Albaicín, Granada); (2) the other method involves layers of earth about 60–80 cm thick, and layers of pure lime about 8–12 cm thick at the ceiling and at the base (example the Arch of the Puerta Elvira in Granada). These constructions date from the 12th and part of the 13th century. The facing on the walls was applied once the formwork frame had been taken down.

B) *Tapial Calicostrado*. This technique appeared as a solution to the damage caused by erosion when the rammed earth was exposed to the elements. Using this method, a crust or finish was formed on the surface of the wall at the same time as the building was being constructed. This was a significant advance on the road to perfecting the rammed-earth technique, as it provided both protection against erosion and an aesthetically attractive finish. The building process followed was similar to that used in other rammed-earth structures, except that a strip of mortar with a higher proportion of lime was applied to the outside and the earth was then trodden down so that the lime mortar became indented in the wall, forming one single structure with the rest of the building (Ontiveros Ortega et al. 1999; Sebastián Pardo 2001).

This form of *tapial* first appeared at the end of the 13th century and reached its peak in the 14th century (e.g., the Arrabal in the Albayzin and other buildings from the Nasrid period in Granada).

Different construction techniques were used at different times in history and as time went by less and less lime was used, something which was perhaps related to the economic decline of the Kingdom of Granada as the Christians conquered more and more of its territories. Less lime meant poorer quality construction as explained below.

2.2 Research into Rammed-Earth Constructions and the Conservation Thereof

Rammed-earth constructions show serious durability problems, caused basically by the nature of their constituent materials (normally considered "poor" building materials), and by the types (mainly clays or lime) and the small amounts of binder used.

Damage to these constructions is normally caused by a variety of different factors and mechanisms, including rainwater, soluble salts from the material itself and/or contained in the water that enters the structure through capillary ascent, oscillations in temperature and, in desert regions, by the particles carried by the wind (Sebastián Pardo and Rodríguez Navarro 1996; Hall and Djerbib 2004, 2006a, b). The restoration of rammed-earth walls is almost always viewed as a question of replacing the damaged parts and there are few reports as to the use of consolidation or water-repellent products (Sowden 1990; Warren 1999; Jayasinghe and Kamaladasa 2007; Pineda Piñon et al. 2007). Chips and erosion dips are normally repaired by creating a support for the cement preferably with mesh (chicken-wire), or moistened pieces of ceramic that are pushed into the wall and act as pivots that stick out from the surface and help the mix used to repair the damage to adhere properly to the wall (ICCET 1987; Naval Mas 1990).

On the basis of these ideas, the objective proposed for this work was to discover a new way of conserving rammed-earth buildings of historical interest by treating them with chemical products, i.e., by impregnating them with consolidants and water-repellents. With this in mind we decided to characterize the constituents of the materials used in two historical buildings, the *Palacio de los Abencerrajes* (Palace of the Abencerrajes) and *Silla del Moro* (Seat of the Moor) otherwise known as Castillo de Santa Elena, situated inside the Alhambra complex.

According to studies by various different authors (Malpica 1992; Salmerón 1999), the *Palacio de los Abencerrajes* probably dates from the 13th century, the first Nasrid period, and is essentially a group of rooms situated at different levels.

There are few references in the specialist literature as to the characteristics and functions of the tower known as *La Silla del Moro*; but it seems likely that it was used as a look-out point, given its excellent position overlooking the valley of the River Darro. The walls of the tower are made from *tapial calicostrado* and the foundations are laid on the rock formation known as the Alhambra Formation that outcrops in the area. This formation is composed of conglomerates with intercalated sands and clays and dates back to the period between Pliocene and Lower Pleistocene. The tower has undergone several restoration attempts that are easy to identify: the first series by the architect Torres Balbas over the first third of the 20th century with masonry; and the subsequent work done by Prieto Moreno, several years later with stones linked together with vertical pilasters and horizontal lines of brick.

2.3 Materials and Scientific Methodology

Samples were taken from the original rammed-earth wall from the Nasrid period in the area of the *Palacio de los Abencerrajes.* It is important to highlight the fact that sampling in archaeological sites such as this one is a problem, as few original pieces remain and those that do are of enormous historical and artistic importance. This means that we were only able to take a few cubic centimetres of samples.

Sampling at the *Silla del Moro* did not pose such a problem as the tower was blown up by the French in September 1812 and large chunks of the original wall are to be found nearby, which enabled us to take more, larger samples.

We also analysed different samples from the outcrops of the Alhambra Formation. These samples were taken from the Cerro del Sol, near the Alhambra.

The techniques and procedures used in this study were those normally used in the granulometric, petrographic (compositional and textural), physical and mechanical characterization of building rock. We also performed accelerated aging tests that enabled us to evaluate the effectiveness of the treatment products we applied. The techniques and procedures normally used in geology, and in particular in mineralogy and petrology, have also been shown to be useful tools for the characterization and study of rammed-earth constructions.

2.4 Results

2.4.1 Granulometric Analysis

We were only able to analyse samples of the *tapial* from the *Silla del Moro* and samples from different levels of the Alhambra Formation. When we analysed the values obtained from the different types of sample, we found that none of them came near the granulometric standards that should be followed in the preparation of concretes used nowadays. In Nasrid times, it would seem that there was no selection process for the materials used in rammed-earth constructions, and they used materials from the different levels of the Alhambra Formation almost as they found them, only discarding the thickest fraction and possibly a small proportion of the finest materials.

2.4.2 Compositional and Textural Study

For the compositional and textural characterization of the materials, we used X-ray Diffraction (XRD), optical microscope and scanning electron microscope (SEM).

The most significant results are those obtained for carbonates (Table 2.1). The values for calcite allow us to state that lime was used in the construction of the original walls, as the proportions of lime encountered are systematically higher than those obtained from the samples from the outcrops of the Alhambra Formation collected nearby. For various reasons it is difficult to establish the exact proportions of lime added. Firstly, because it is impossible to distinguish what proportion of the calcite was originally an aggregate and what was originally lime (after the mix sets and goes hard, the lime is converted into crystals of calcite). The amounts added seem to vary depending on the particular part of the wall analysed, with less lime

Table 2.1 Results of XRD analysis of samples collected in the *Palacio de los Abencerrajes* (ABEN) and *Silla del Moro* (SMO)

	Qtz	Cal	Dol	Phy	Fds	Gyp	Port
ABEN2	30	55	tr	10	tr		
ABEN3	35	40	tr	15	10		
ABEN4	45	35	tr	15	5		
ABEN5	10	90					
ABEN6	35	45		15	5		
ABEN7	45	40	tr	10	5		
SMO1	40	10	20	25	5	tr	x
SMO2	45	25	5	20	5		x
SMO3	30	30	5	10	5	20	x
SMO4	45	15	35	tr	tr	5	x
SMO5	35	15	10	35	tr	5	x
SMO7	50	25	15	10	tr		x
SMO8	25	20	5	45	5		x
SMO9	50	30		15	5		x
SMO10	50	40		10	tr		
SMO11	55	5	5	30	5		x
SMO12	55	40		tr	5		
SMO13	45	25	10	10	tr	10	
SMO14	30	30	10	25	5		
SMO16	50	30	5	10	5		x
SMO17	45	25	15	tr	5	10	
SMO18	30	15	35	15	5		
SMO19	65	25	tr	5	5		
SMO24	45	25	15	10	tr	5	
SMO1-1	60	25		5	10		
SMO1-2	60	25	tr	10	5		

Legend: Qtz = quartz; Cal = calcite; Dol = dolomite; Phy = phyllosilicates; Fds = feldspar; Gyp = gypsum; Port = Portland cement; "tr" means traces; "x" means that this phase has been detected

used for the inside of the wall than for the outside; they also vary according to the period in which they were constructed and the function of the building. The samples taken from the *Palacio de los Abencerrajes* contain higher quantities of calcite, which means that larger amounts of lime-binder were added, around 30%. While in the *Silla del Moro*, the walls were cemented with much lower amounts of lime (15–20%).

Another contrast was that there was almost no dolomite in the walls of the *Palacio de los Abencerrajes*, while traces were found in almost all of the samples from the *Silla del Moro* (Table 2.1). It is important to point out that in other parts of the Alhambra complex and in other pre-14th century Muslim buildings in Granada, no dolomite can be found in the aggregate (whereas in modern buildings in the city, it is almost the sole constituent of the aggregate).

Another important result was that we found traces of Portland cement in several samples (Table 2.1). As this product was not used in building until the end of the 18th century, it means that these samples must come from the restoration work carried out by Torres Balbas or Prieto Moreno. It was only identified in the samples from the *Silla del Moro*, and not in those from the *Palacio de los Abencerrajes*.

There are two further interesting aspects of the materials from the *Silla del Moro*: (1) gypsum was identified in several samples; and (2) phyllosilicates were discovered in higher percentages than in the other samples analysed. The gypsum could come from the cement itself, as it was added to the cement in the factory to delay the setting process, or it could be produced as a result of reactions with the other materials, with the gypsum being the product of the migration of ion-rich solutions inside the wall.

The high proportions of phyllosilicates suggest that either Torres Balbas or Prieto Moreno used the Alhambra Formation as an aggregate in the mortars used in the restoration work (as did the Arabs) to ensure among other things that replacement materials had a similar colour to that of the original structure. It would seem however that the process was carried out without selecting the material.

2.4.3 Polarization Optical Microscope Examination

We prepared thin layers from samples that showed sufficient consistence, as this type of material is very fragile and the samples often fall apart during the cutting process.

In terms of composition we were able to distinguish two basic types of aggregate: a carbonated aggregate formed by mainly rounded grains of calcite and/or dolomite; and a siliceous aggregate, made up of normally subangular fragments of different kinds of metamorphic rock: quartzites, schists, amphibolites.

The following points are worth noting with regard to textural aspects of the samples: petrographical observation showed that the binder was formed by fine-grain calcite, although in some areas it appeared in recrystallized form (Fig. 2.2a). There was a large amount of aggregate with subangular or rounded grains of all sizes from very fine to very thick (several centimetres). This was basically made up of quartzite and schists. The adherence between the aggregate and the binder was good (Fig. 2.2b). The matrix, composed of calcite and phyllosilicates, was not very well mixed in some areas. We also observed nodules of clays and other areas that were rich in lime. Porosity was normally very high with pores that were normally round and on occasions showed cracks.

The original plasterwork was a very pure uniform lime stucco that was made up almost exclusively of calcite. The pores were rounded and poorly communicated. Fissures could be observed running parallel to the outer surface; an ochre-coloured layer had formed on the outside.

2.4.4 Scanning Electron Microscope Analysis

The SEM showed how the aggregates were perfectly encased in the matrix formed by the calcite crystals which surrounded them completely. These crystals came

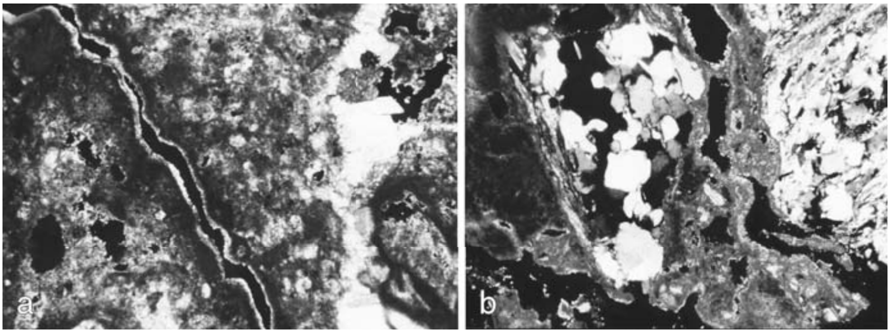

Fig. 2.2 Optical microscopy of some samples where binder and aggregate components can be seen

from the lime that had been transformed into calcium carbonate. In other cases, we observed that the calcite appeared as a mosaic of well-formed crystals, especially when it was located in pores and fissures. In this case the crystals were produced either by the dissolution and subsequent crystallization of the original calcite from the aggregate or by the carbonation of the lime.

In other areas, the lime looked powdery and had large cracks, which could be the cause of the damage that we observed at a macroscopic level. There were other areas that showed considerable damage. These sometimes contained gypsum (and other salts) that normally crystallizes in tabular form.

2.4.5 Physical and Mechanical Parameters

Table 2.2 shows the various physical and mechanical parameters we calculated for the samples of *tapial*. The results shown are the average values for several readings.

We should emphasize that it is very difficult to establish the mechanical parameters of this kind of material, as the rules for the experiments (as there are no official standards for rammed-earth structures, we normally use the standards for cement mortars or concrete) require large volumes and a large number of samples (requirements which we have been unable to meet in this work for the reasons explained

Table 2.2 Physical mechanical parameters of rammed-earth and modern concrete/mortar samples

	ρ	P	$\varnothing$	σ_C	σ_T
Rammed-earth	2.02	>35%	1–15	2.1	0.2–0.3
Concrete/mortars	2.15	<20%	<1	8.2	1.1

ρ = apparent density (g cm^{-3}); P = porosity (%); $\varnothing$ = pore range (µm); σ_C = resistance to compression (MPa); σ_T = resistance to traction (MPa) above). This means that the values set out in the table should be viewed with some degree of caution.

The highest density was in the *Palacio de los Abencerrajes*. The average pore access radius was between 0.7 and 5 µm; the open porosity values varied from 30 to 35% in the areas with low doses of lime (the innermost part of the wall); while in the case of the mortars used in the restoration work on the *Silla del Moro* (20th century), the values were less than 20% and microporosity was the dominant feature.

There are also marked differences between the mechanical resistance of the original samples (2.1 MPa) and the materials used in the restoration work, which is four times higher (8.2 MPa). This is another parameter that can help us to distinguish between the two materials when there are doubts as to whether the *tapial* is original or not. The traction values are very low (0.2–0.3 MPa), but this is only to be expected if we bear in mind that the union between the clasts was made with a binder (lime or clays) with relatively limited binding power.

2.5 Consolidation and Protection Procedures and Treatments

An essential objective of this work is to impregnate samples of *tapial* from historic buildings with chemical products and then evaluate how suitable and how effective they are. The products we applied were Tegovakon V (Tk) and Tegosivin HL100 (Tg), both manufactured by Goldschmidt Industrial Specialities. These treatment products were selected because of their composition. The first is an ethyl silicate (an organosilicic product of the alkoxysilane type) which polymerizes inside the material and is converted into silica. This cements the material together so consolidating the structure. It is therefore a product with considerable chemical affinities with the silicated materials that form the main constituents of these rammed-earth structures. Tegosivin HL100 is a silicone resin with a water-repellent effect. We carried out the treatment by immersing the samples completely in the product, which in the case of Tegosivin HL100 was dissolved in Toluene (Tg concentration of 10%).

The penetration of these products in the samples was calculated by measuring the increase in weight. Although the weight increase was never particularly notable it was slightly higher in the samples from the *Silla del Moro* (these figures must be viewed with a lot of caution, as pieces of material break off very easily in the liquids, leading to a loss of weight that offsets the weight increases caused by the successful penetration of the treatment product).

2.5.1 Techniques and Experiments to Evaluate the Effectiveness of the Treatments

We also noticed that the samples had undergone chromatic change during the treatment (Table 2.3). They went noticeably darker when the consolidant (Tk) was

Table 2.3 Lightness and chromatic coordinates (a* and b*) calculated for samples without treatments and treated with Tegovagon V and Tegosivin HL100, using illuminant C

	Without treatments			With Tegovakon V			With Tegosivin HL100		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
ABEN2	66.96	0.06	3.69	59.78	0.36	5.06	67.20	0.08	4.04
ABEN3	66.27	0.33	8.13	63.29	0.25	8.10	68.71	0.13	6.11
ABEN4	74.67	0.14	4.83	67.24	0.55	8.08	71.74	0.38	5.77
ABEN7	70.43	0.26	4.59	63.15	0.65	7.46	67.43	0.23	4.76
SMO14	65.14	1.77	9.22	57.61	2.44	11.24	62.14	1.92	10.12
SMO19	65.15	3.14	8.56	53.46	5.51	12.09	59.82	3.87	11.25
SMO24	63.71	2.12	7.83	53.06	3.39	10.57	57.23	2.57	9.44
SMO1-1	58.93	3.85	12.18	50.87	4.40	12.77	54.12	3.64	11.58
SMO1-2	73.79	2.72	11.24	64.90	1.18	13.14	66.23	1.19	13.77

applied and the same thing happened albeit to a lesser degree when the water-repellent (Tg) was applied. In all cases however the samples began to recover their original colour after a few days of drying-out.

We calculated the numeric values for the chromatic parameters a* and b* and the lightness figure L* using a Minolta CR-210 colorimeter, which allowed us to describe the colour of the *tapials* in a quantitative way and so evaluate the effect of the treatment products on the samples.

Tk provides similar results to those for the wet samples, in terms of the variation in the primary stimuli a* and b*. Tg causes only very minor changes (Table 2.3).

2.5.2 Scanning Electron Microscope (SEM)

Surprisingly, the SEM showed that the treatment products had penetrated the samples quite well. We identified pores that were covered in consolidant (Tk) at a depth of 2 cm (Fig. 2.3a). We observed that not only had the consolidant coated the pores, but it had also impregnated the whole sample, including the matrix of clays and lime, a sign that it had performed well.

The consolidant also significantly reduced the porosity level (as can be seen in Fig. 2.3b). This big fall in the porosity level could have a negative effect in terms of the success of the treatment, because if the consolidant sealed the surface completely, it would prevent the normal transpiration of the humidity in the wall, which in the medium term could cause serious damage.

The water-repellent produced numerous retraction fissures of different sizes on the surface, forming polygonal-shaped layers of about 100 μm (Fig. 2.3c), some of which adapted to the morphology of the crystal over which they ran. We also observed pores produced by the release of gas bubbles which would enable some evaporation of the humidity from the inside of the wall (Fig. 2.3d). The treatment achieves a noticeable reduction in surface porosity.

The water-repellent normally appears as a very fine film (approximately 0.5 μm) that covers the majority of the clasts and the binder without penetrating very far into the *tapial* sample.

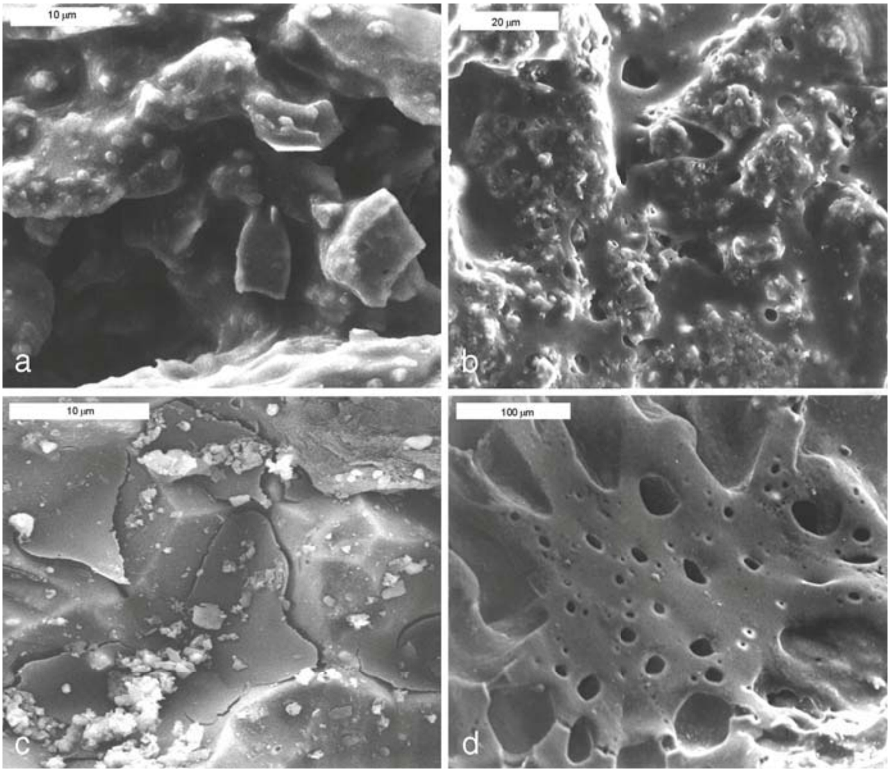

Fig. 2.3 SEM images of rammed-earth samples treated with Tegovakon V (**a** and **b**) and Tegosivin HL 100 (**c** and **d**)

2.5.3 Hydric Tests and Porosimetry

We also carried out hydric tests to evaluate the effectiveness of the treatments. The fact that these samples are very fragile and lack cohesion made it very difficult for us to perform these tests. The majority of the samples fell apart when placed in water for a short period of time, sometimes within just a few minutes. This even happened with the samples treated with consolidant or water-repellent products.

In the absorption test the untreated samples behaved very differently from the samples that had been treated with Tk or Tg. The untreated samples absorbed large amounts of water fast as shown by an increase in their weight. This process occurred over the first 5 min of the test, after which the weight of the sample stabilised and only minimal changes occurred. In some cases weight reductions occurred due to the fact that part of the material broke off when submerged in the water.

The absorption kinetics of the treated samples was very different, with water absorption occurring much more slowly, as manifested in a very slow increase in weight. At the end of the process the water absorption coefficient was less than 5% (in the untreated samples, this figure was around 12%). There was a clear difference between the group of samples treated with Tk and the samples treated with Tg. The latter showed considerably lower water absorption coefficients. It was impossible for us to observe any differences between the samples from the *Palacio de los Abencerrajes* and the *Silla del Moro*, as only one sample from the *Silla del Moro* survived the test.

We deduced that desorption of water was constant, as within a few hours the samples had returned to their original pre-experiment weight, and sometimes even fallen below it. This confirmed once more that the material lacked cohesion, even when treated with consolidant products.

A very important result is that desorption of water did not seem to be blocked by the treatment, as the desorption curves were very similar for the treated and untreated samples. In general, they shed water (dried out) very quickly. Although in the case of the curves for samples treated with one of the products the slope is less inclined, this could imply that the level of porosity has changed, possibly because of a reduction in the diameter of the capillaries that link the large pores. This is even clearer when the product applied is the consolidant.

2.5.4 Density and Porosity

The figures for effective porosity, and the figures for apparent density and surface area were calculated with a mercury intrusion porosimeter (Micromeritics Autopore III 9410).

In all cases the treatments provide a relatively limited reduction (between 10 and 20%) in the effective porosity of the samples, except in the sample from the *Palacio de los Abencerrajes* (porosity fell by 33% with Tg). The values for specific surface and apparent density vary greatly from one sample to another, and no clear tendency can be observed for the treatments. This is one more in a series of facts that confirm the obvious heterogeneity of these rammed-earth structures.

2.5.5 Accelerated Aging Tests in the Laboratory

We performed two different accelerated aging tests using salt crystallization cycles and freeze-thaw cycles. The destructive effects of these two tests are of a physical nature. The results obtained in these tests were mainly based on differences in weight before and after the successive cycles. They were complemented with macroscopic observations of the damage to the samples.

2.5.5.1 Salt Crystallization Tests

The test was carried out according to the UNI EN 12370 Standard (2001).

The samples treated with the consolidant Tk suffered sharp weight loss from the 4th cycle onwards, and one sample fell apart completely during this cycle. This was especially true in the case of the samples from the *Silla del Moro*. The damage began in the area where the clasts and the matrix joined, and they came apart very easily. Another important aspect is that most of the pieces that break off are parts of the matrix. As they fall off, the larger, more resistant clasts are laid bare, so creating the typical uneven appearance of the damaged rammed-earth structure.

Most of the samples from the *Palacio de los Abencerrajes* gained weight (slightly) during the first few cycles. This increase then waned and by the 5th and 6th cycle the samples fell below their initial weight. These samples passed through all the cycles without breaking up and no salts crystallized on their surface.

The samples treated with the water-repellent (Tg) behaved in a somewhat different way. Their weight increased at the beginning of the test, indicating that salts had crystallized inside them, possibly because the porous system had changed in such a way as to prevent the salt solution from coming out of the samples during the drying phase. In some cases there was a significant reduction in weight at the end of the test (around 10% after 10 cycles). The samples from the *Palacio de los Abencerrajes* also showed better results with this product (Tg).

2.5.5.2 Freeze-Thaw Tests

There are different standards laying down the procedure to be followed in this type of test (RILEM, ASTM, UNE,…) In this work we followed the UNI EN 12371 standard (2003).

We observed during this test that almost all the samples performed badly (irrespective of whether they had been treated with the consolidant or the water-repellent), as from the 6th or 7th cycle onwards (some samples even earlier) they began to lose weight; in most cases to a significant degree. Some samples (mostly from the *Silla del Moro*) fell apart completely before the 10th cycle, while others lasted for 20 or 25 cycles before finally breaking up. The only samples that managed to complete the whole test (30 cycles) were the two samples from the *Palacio de los Abencerrajes* treated with Tg, which at the end of the experiment had lost between 6 and 8% of their weight.

In this accelerated aging test, the samples from the *Silla del Moro* were once again shown to be less durable than the other samples. In short, we should stress the fact that the samples from the *Palacio de los Abencerrajes* were in general more durable than those from the *Silla del Moro*. This is because they have a higher proportion of binder (lime) and also to a lesser extent because the grain size of the materials from the *Palacio de los Abencerrajes* was more carefully selected (the *tapials* from this monument do not normally contain overly large stones for example).

2.6 Conclusions

The *Tapiales* constructed in the Nasrid period did not conform to present-day building standards at least in terms of the ideal or correct granulometry of the aggregate. The available information suggests that the sedimentary stone from the Alhambra Formation was used more or less as it came, with only about a third being rejected (the thickest fraction and possibly a small proportion of fine aggregate).

The mineralogical and petrographic study of the samples shows that the *tapial* was made up of a mixture of detritic material (lutites, sand, and stones of varying sizes), and slaked lime. The proportion of lime varies depending on which part of the wall the sample is taken from, and on the importance of the building and the historical period in which it was built. On the basis of the results obtained in this work and in a previous study (de la Torre et al. 1996) the proportion of lime in the *Palacio de los Abencerrajes*, is around 25–30%, while in the *Silla del Moro* it is less than 20%.

In all cases, the lime used is very magnesium-poor (fat lime) which leads us to the conclusion that they carried out a pre-selection of the rock they were going to fire to obtain the lime. We can also conclude that the lime added to these *tapials* was good quality lime. The aggregates used were siliceous (especially pebbles from metamorphic rocks) and/or carbonated, and only rarely were dolomite pebbles used. It would therefore seem that they also made a careful selection of the aggregate they were going to use.

As these are building materials with a very heterogeneous internal structure, rich in clays, with a relatively low proportion of lime and which have lost their original protective coating, it is necessary to treat them with consolidant or water-repellent products that can prevent their progressive decay. This decay is caused by a wide variety of factors, the most important of which is water. Damage is caused both by rainwater and by the water that ascends by capillarity from the ground and which may contain high proportions of soluble salts. The damage is produced mainly by contact between matrixes and clasts, due to the fact that any interface between two different materials is a potential weak zone. If conservation treatment is not applied to these rammed-earth structures (especially those in the *Silla del Moro*) they will probably fall into a ruinous state in a relatively short time.

The heterogeneity of the samples taken from different points of the walls can influence the degree of damage they are likely to suffer in the accelerated aging tests in the laboratory. The samples in which the aggregate has a maximum size of just a few millimetres resist the accelerated aging tests relatively well, while the samples with aggregate containing larger pebbles of a centimetre or more in diameter break up quite quickly.

In spite of their heterogeneity and their lack of cohesion, the samples we studied absorbed all the treatment products quite well. SEM examination showed that the consolidant impregnated the *tapial* to a depth of 2 cm, a perfectly acceptable result.

The consolidation and protection products analysed in this study were both effective. All the treated samples performed much better in the hydric tests than the untreated samples, absorbing about 50% less water. In addition, the water absorbed was soon lost as the samples dried out. They also performed well in the accelerated aging test using salt crystallization. No external changes were observed in this test with just scattered salt crystallization in some of the samples.

We should also mention that the application of these products leads to chromatic changes in the samples, especially when the product contains ethyl silicate. In the samples treated only with the silicone resin, the change in the colour is much slighter and the original colour is recovered more quickly. In all cases however, the samples gradually recover their original colour. Samples treated with the consolidant acquired a sheen, which also disappeared gradually when in contact with water. This suggests that these undesirable aesthetic effects (unacceptable in a historic monument such as the Alhambra) would disappear upon exposure to the natural elements in our atmosphere, without this implying any loss of effectiveness.

We would like to finish by proposing possible future lines of research for this building material. More detailed analysis of the chemical, physical, and mechanical behaviour of earth as a building material is required and of its interaction with the environment, in order to be able to develop conservation techniques that are as non-invasive as possible and to devise more effective maintenance procedures.

Another question that must be analysed and evaluated is the damage that can be caused by the use of materials that are unsuitable for the conservation/restoration of rammed-earth buildings. Research into the most suitable products or materials for the conservation of these buildings must also be carried out.

Finally, we must bear in mind that most repair work on rammed-earth buildings must be classified as restoration work in which it is normally decided to substitute or replace the parts of the building suffering from serious damage. It is therefore necessary to study which quarries can supply the best aggregate for the work, so as to ensure that the aggregate selected has the best possible granulometry, composition, and chromatism and that it is compatible with the other materials used. The nature and the quality of the binder to be used in the work must also be studied beforehand. We recommend that fat lime should be the only binder used.

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Chapter 3
Ancient Clay Bricks: Manufacture and Properties

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3.1 Introduction

Clay brick masonry is one of the oldest and most durable construction techniques used by mankind. Masonry consists of manually built stable stacks of small elements, with or without mortar. It was a fundamental building material in the Mesopotamian, Egyptian and Roman periods. During the Roman period, the use of clay brick increased and became specialized in order to maximize its benefits. Clay brick masonry continued to be used during medieval and modern times. Despite several modifications of the clay brick uses, shape and manufacture along thousands of years of constant evolution, the simplicity that made its success remained.

Numerous buildings built with clay bricks prevailed until the 21st century, which testifies to the strength of this material along centuries of rain storms, snow, thaw-freezing cycles, high temperatures and human induced deterioration. Moreover, brick could be easily, inexpensively and rapidly handled and produced with a simple manufacturing process. It is based on fired clay, a raw material available in large quantities all over the Earth. Its wide use proved that clay brick was an effective construction material that could provide both resistance to prevalent climatic conditions and insulation from cold and heat.

It is known that the properties of ancient clay brick masonry rely essentially on the properties of the brick units, which depend on the quality of the raw materials used, together with the manufacturing process technology. The analysis of clay brick production and final properties are therefore fundamental. Generally, it is crucial to obtain information on the main physical, chemical and mechanical properties of clay bricks as well as the characteristics of the raw materials used and their manufacturing process.

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A large number of studies exist dealing with ancient structures and materials, fostered by the immense cultural and economic importance given to ancient monuments. Most of them have focused on the physical, chemical and mineralogical composition of ancient clay bricks (López-Arce et al. 2003; Cardiano et al. 2004; Pauri et al. 1994), durability and deterioration agents (Wijffels and Nijland 2004), neglecting the mechanical properties, which are more frequently retrieved in the case of the composite material (Binda et al. 2000a). Despite the importance of mechanical properties and its relevance for the resistance and durability of masonry, only a few of the published studies focus on the mechanical properties of clay bricks (Papayianni and Stefanidou 2000; Baronio and Binda 1985). In fact, the compressive strength of clay bricks is usually related to other properties, such as porosity and firing temperature, which are key parameters for durability (Cultrone et al. 2000) but can markedly affect the mechanical resistance of bricks (Cultrone et al. 2004).

As the properties of ancient bricks vary considerably in terms of raw materials, production methodology and period, attention here is paid to clay brick production and analysis of its properties in numerous examples recovered from a literature study and from samples of old bricks taken from six Portuguese monuments (Church of Outeiro, OU, Monastery of Pombeiro, PO, Monastery of Salzedas, SA, Monastery of São João de Tarouca, TA, Monastery of Tibães, TI and the Christ Cloister in Tomar, TO) dated to the period of 12th–18th centuries. The main physical, chemical and mechanical properties were determined.

Instead of the laboratory testing of highly invasive uniaxial compressive strength, a new on-site minor-destructive-technique to assess the drilling resistance of old clay bricks was tested.

3.2 Manufacturing Process

The manufacture of fired clay bricks can be divided into four stages according to basic principles followed during thousands of years. Firstly, the extraction and preparation of the raw clay takes place. As soon as the raw material is extracted, it is accumulated and moved to an open air storage area. During this period, the raw material is rummaged in order to reduce soluble salts to a minimum, leading to a more homogeneous material. The analysis of the constituents of historic bricks that have survived up until our day showed that they were not always produced using treated clays. In some cases, bad quality clays were used. Vitruvius (1960) stated, in the 1st century B.C., that the choice of the raw material was essential to improve the performance and durability of the bricks. Despite this fact, the selection of raw materials depended mostly on its availability at the construction location or nearby (Álvarez de Buergo and Limón 1994).

After storage, clay is further crushed and mixed with water, in an operation designated as tempering. In the early times, the mixing was carried out by hand, in a crude and often ineffective manner; but, later, horse-driven heavy rollers or wheels in a ring-pit were used. The amount of water used depends on the type of element being produced and, usually, smaller and thinner clay elements would require a greater amount of water. The resulting mix must be characterized by enough plasticity to facilitate the molding, but not "too plastic", as it can lead to severe shrinkage during the drying phase, resulting in warping, twisting or cracking. In this case, plasticity of the clay can be reduced adding sand, for example. Early brick makers often used a mix of about 30% of sand and 70% of plastic clay (Weaver 1997; Vekey 1998). The moulds in the past were bottomless wooden moulds placed down over the ground or over tables, which usually were protected with a thin film of sand in order to avoid letting the brick remain attached to the bottom base during the drying process. The excess clay was removed with the aid of a rope, wooden ruler or with bare hands.

The still crude clay elements were removed from the mould and dried in a covered space, which was generally a shelter made of scraps of wood and with a straw thatched roof: these shelters were known as hovels. Although inexpensive, this primitive method required a lot of open free space and was severely conditioned by climatic conditions. Generally, drying of clay bricks lasted for a week or more. In hot temperature regions, drying was faster but bricks had to be protected from direct sunlight since they could undergo warping and cracking. In colder regions, drying took more time due to the low temperatures and moisture conditions. The importance of the drying phase was mentioned by Vitruvius, who wrote that "bricks should be made in Spring or Autumn, so that they may dry uniformly". Moreover, a too fast drying hardened the surface faster than the core, which remains crude for a longer time. Again, Vitruvius stated that bricks "made in summer are defective, because the fierce heat of the sun bakes their surface and makes the brick seem dry while inside it is not dry".

Finally, the last stage was the hardening of the bricks in order to acquire additional resistance. Bricks were further sun dried, in the open air, or were put in a kiln or clamp with temperatures in the order of 1,000ºC, where they were fired, acquiring in this way much more resistance from both a mechanical and chemical point of view. Early kilns used wood or straw as combustibles and took several days to finish combustion. Coal was not commonly used until the last quarter of the 19th century. During this phase, complex chemical reactions took place, creating diverse ceramic products, according to the firing temperature and the quality of the clay. The firing conditions were crucial for the final properties of bricks, whose quality strongly affects the strength and durability of the masonry. According to Vitruvius, sun-dried clay bricks needed a minimum of two years to dry. To illustrate this statement, he gave the example of Utica, where the clay bricks used to build the walls had to be five years old. Here, attention is focused on fired clay bricks only.

3.3 Properties of Fired Bricks

Clay bricks exhibit a set of properties that are important in the evaluation of strength and durability. The properties are closely related to the quality of the raw clay and directly associated with the conditions of manufacture.

When working with old clay bricks, additional parameters related to weathering mechanisms, material ageing and long term effects must be considered, like cracking, peeling or efflorescence. These effects are usually increased by atmospheric agents such as wind and water. Thus, the properties exhibited today by old clay bricks do not necessarily represent their original properties.

Nevertheless, the physical, mechanical, chemical and mineralogical parameters are relevant to the evaluation of the durability and resistance of old clay bricks.

3.3.1 Physical Properties

3.3.1.1 Porosity

Firing of clay bricks produces a series of mineralogical, textural and physical changes that depend on many factors that influence porosity. Porosity can be defined as the ratio between the volume of void spaces (pores and cracks) and the total volume of the specimen. Porosity is an important parameter concerning clay bricks due to its influence on properties such as chemical reactivity, mechanical strength, durability and the general quality of the brick.

Old clay bricks exhibit high porosity values, ranging between 15 and 40 vol.% (Esbert et al. 1997). The porosity of bricks from the Byzantine period was reported to be between 15 and 35 vol.%, while 70–80% of the pores had a diameter size of 70–250 μm, independently of the type and origin of the clay (Papayianni and Stefanidou 2000). Livingston (1993) reported that the porosity of bricks in the Church of Hagia Sophia is in a range of 26–30 vol.% for the red coloured bricks and 40–55 vol.% for the beige ones; while Maierhofer et al. (1998) obtained porosity values between 21 and 35 vol.% in bricks from the 9th–10th and 13th centuries, respectively. Fernandes (2006) reported the value of porosity of clay bricks from the 12th to 18th centuries as ranging from 12 to 43 vol.% with a mean value of 18 vol.%. In this case, around 80% of the samples exhibited a porosity larger than 25 vol.% and the vast majority between 25 and 35 vol.%, as illustrated in Fig. 3.1.

The dimension and distribution of the pores is influenced by the quality of the raw clay, the presence of additives or impurities, the amount of water and the firing temperature. Mamillan (1979) and Cultrone et al. (2004) observed that if the firing temperature increases, the proportion of large pores (3–15 μm) increases and the connectivity between pores is reduced, whereas the amount of small pores diminishes. This has a strong impact on the durability of the bricks as it has been shown that large pores are less influenced by soluble salts and freeze/thaw cycles. Furthermore, several studies by Cultrone et al. (2004) and Elert et al. (2003) reported that the formation of small pores, with a diameter below 1 μm, is promoted by carbonates in the raw clay (low quality material) and by a firing temperature between 800 and 1,000°C. Such pore sizes negatively influence the quality of the bricks, as their capacity to absorb and retain water increases. A similar conclusion was given by Winslow et al. (1988) for bricks with a pore size smaller to 1.5 μm.

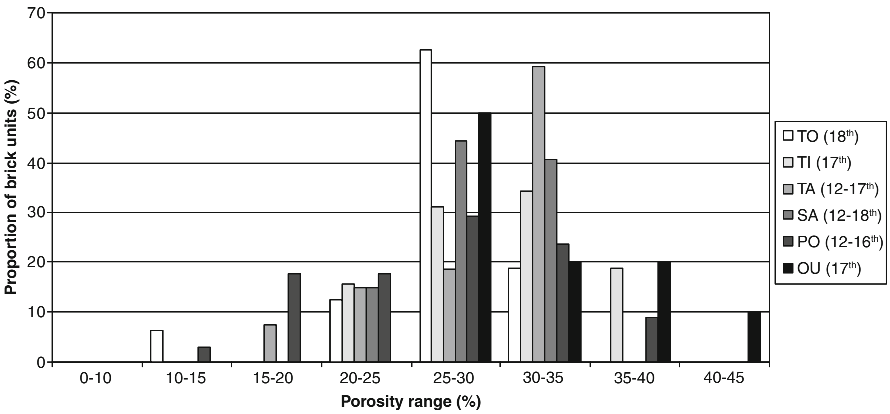

Fig. 3.1 Distribution of porosity for the complete set of clay bricks (Fernandes 2006)

3.3.1.2 Apparent Density

Apparent density is described as the ratio between the dry brick weight and the volume of the clay brick, measuring the proportion of matter (clay) found in the volume. It is evident from this description that the higher this value is, the denser the brick is, and obviously, the better its mechanical and durability properties are. Typical values for the apparent density range from 1,200 to 1,900 g m^{-3} (Table 3.1).

3.3.1.3 Water Absorption

Pores constitute a large part of the brick's volume, and when the bricks are exposed to rainfall or rising damp, water generally penetrates into the pores. Water absorption then determines the capacity of the fluid to be stored and to circulate within the brick, favouring deterioration and reduction of mechanical strength. In countries where temperatures fall below 0°C, the water inside the pores can freeze leading to surface delaminations, disintegration or cracking. Moreover, in the presence of soluble salts, water tends to react with them and to cause efflorescence. Though this is mostly an aesthetic deterioration of the surface of the brick, the volume increase caused by the crystallization of the salts can cause severe damage.

The values found in the literature are significantly scattered, with a large quantity of bricks with higher than average water absorption rates. Binda et al. (2000b) reported different absorption rates with respect to the colour exhibited by 8th–13th century bricks from the bell-tower of the Cathedral of Cremona, Italy. Brown and red bricks were found to have a water absorption of about 20.1 and 24.9 wt.%. In bricks from the 9th–10th centuries, values of water absorption between 18 and 19 wt.% were found, whereas values of 12 and 24% were attributed to bricks from the 13th century (Maierhofer et al. 1998). Moreover, clay bricks from the 12th to 18th centuries (Fernandes 2006) exhibited values between 6 and 32 wt.%,

Table 3.1 Typical values of apparent density of old bricks

Period (century)	Monuments and their location	Apparent density ($kg\ m^{-3}$)	References
1st–5th	Walls, pillars, vaults and ovens of buildings	1400–1900	Papayianni and Stefanidou (2000)
3rd–4th	Church of S. Lorenzo, Milan, Italy	1550–1650	Baronio et al. (1985), Baronio and Binda (1985)
6th	Basilica of Hagia Sophia, Turkey	1600–2000	Livingston (1993)
9th–10th	Bricks of the Church of S. Maria Rossa	1600	Maierhofer et al. (1998)
12th–13th	Bricks from the city of Toledo, Spain	1600	López-Arce et al. (2003)
13th	Bricks of the Church of S. Maria Rossa	1830	Maierhofer et al. (1998)
13th–14th	Bricks from the city of Toledo, Spain	1510	López-Arce et al. (2003)
12th–16th	Monastery of Pombeiro	1680–1840	Fernandes (2006)
12th–17th	Monastery of São João de Tarouca	1710–1820	Fernandes (2006)
15th–16th	Church of S. Maria Incoronata, Milan, Italy	1550–1850	Baronio and Binda (1985)
16th	Clay bricks from Italian buildings	1550	Bati and Ranocchiai (1994)
17th	Church of Outeiro	1700–1780	Fernandes (2006)
17th	Monastery of Tibães	1680–1790	Fernandes (2006)
17th–18th	Cloister of the Church of S. Eustorgio, Milan, Italy	1650	Baronio and Binda (1985)
18th	Monastery of Salzedas	1550–1870	Fernandes (2006), Lourenço et al. (2000)
18th	Christ Cloister in Tomar	1560–1800	Fernandes (2006)

with an average value of 17 wt.%, and more than 90% of the values in the range 10–25 wt.%.

Another relevant parameter is the velocity of water absorption, measured by suction rate. The water is sucked by the pores as a result of capillary tension along the walls of the pores. López-Arce et al. (2003) pointed out that tension is stronger in small pores than in large ones. Generally, old bricks exhibit absorption values between 0.5 and 3.5 $kg\ m^{-2}\ min^{-1}$, which were further confirmed by Fernandes (2006), who reported values in the range 0.7–2.5 $kg\ m^{-2}\ min^{-1}$.

3.3.1.4 Moisture Expansion

The expansion or shrinkage observed in clay bricks can be partially or totally reversible due to wetting/drying, being not so relevant for old clay bricks. Moisture expansion in clay bricks is influenced by the contents of argillaceous minerals and by the presence of lime nodules. Typical values of 0.1–0.2% were indicated by Álvarez de Buergo and Limón (1994) and Esbert et al. (1997).

3.3.2 Mechanical Properties

Masonry is a heterogeneous material, and therefore its compressive strength depends on the strength of the components: brick, mortar and brick-mortar interface. Nevertheless, experimental results indicate that masonry compressive strength is mostly influenced by the strength of the brick units. Therefore, brick mechanics is very relevant to the safety assessment of existing brick masonry structures. The mechanical properties of old bricks are frequently reported in the literature, so it is possible to gather a large amount of data.

In traditional masonry shapes, such as columns, walls, arches and vaults, bricks are mostly subjected to compressive stresses. The adopted structural shapes for these elements make full use of properties of clay bricks, namely reasonable strength in compression and low strength in tension.

3.3.2.1 Compressive Strength

Compressive strength is strongly influenced by the characteristics of the raw material and by the production process. It is known that the raw clay of old bricks was often of low quality and the manufacturing process was relatively primitive and inefficient. Other characteristics of existing old bricks can provide an indication about compressive strength, such as mineral composition, texture, crack pattern and porosity level, by revealing the conditions of drying and firing.

On the other hand, the evaluation of the mechanical strength of bricks belonging to old buildings is often difficult due to the high variability in production and additional variability caused by deterioration from the weather or chemical agents such as soluble salts, freeze–thawing cycles or load–unload cycles. Moreover, clay bricks in a given structural element or building can belong to different construction periods or productions. Finally, the experimental test set-up conditions (dimensions and moisture content of the sample, boundary conditions, temperature, etc.) can also influence the results. According to Pauri et al. (1994), the original properties of old clay bricks would only be obtained through the manufacture of bricks using traditional methodologies and raw materials recovered from indications in archives, which is impossible. The range of values found in the literature is quite wide (about 1.5–32 MPa), meaning that in situ testing or destructive testing of samples must be carried out when the compressive strength of the brick is required. Typical values of the compressive strength are reported in Table 3.2, even though they have been obtained using different testing equipments and procedures.

A wide range of compressive strengths was reported by Fernandes (2006) on clay bricks from six monasteries in Portugal that were built during the 12th–18th centuries period. The selection of the buildings was made according to the works being carried out by the University of Minho in these locations, and as a means to provide a broad knowledge on Portuguese clay bricks. It must be noted that most bricks were collected from vaults, buried remains, soil deposits and infill material, while clay bricks from two particular monasteries were obtained from building

Table 3.2 Typical values of uniaxial compressive strength and modulus of elasticity of old bricks

Period (century)	Monuments and their location	Uniaxial compressive strength (MPa)	Modulus of elasticity (GPa)	Reference
1st–5th	Walls, pillars, vaults and ovens of buildings	9.2–18.0	n. d.	Papayianni and Stefanidou (2000)
1st–5th	Monuments from the Byzantine period	n. d.	2.6–10.8	Papayianni and Stefanidou (2000)
8th–13th	Bell-tower of the Cathedral of Cremona, Italy	8.0–25.4	1–4.4	Binda et al. (2000b)
11th–13th	Vaults of Our Lady Monastery, Magdeburg, Germany	13.1–14.1	n. d.	Marzahn et al. (2004)
13th–17th	Siena's exterior wall, Italy	27.9	5.8	Barbi et al. (2002)
15th	Pienza Episcopal Palace, Italy	n. d.	7.3–18.6	Barbi et al. (2002), Bati and Ranocchiai (1994)
15th	Colle Val d'Else exterior wall, Italy (1479)	19.9–30.0	4.1	Barbi et al. (2002), Bati and Ranocchiai (1994)
16th	Hospital of Las Cinco Llagas de Sevilla, Spain	14.3–32.9	n. d.	Barrios et al. (2000)
	Monastery of Monte Oliveto Maggiore library wall, Italy	31.1	6.3	Barbi et al. (2002)
	Bell-tower of the Cathedral of Monza, Italy, (1592–1605)	4.0–12.0	n. d.	Binda et al. (2000a, b)
17th	Salzedas monastery vaults, Portugal	5.2	7.3	Lourenço et al. (2000)
18th	Lazzaretto de Ancona, Italy (1733)	18.5	4.2	Barbi et al. (2002)
18th–19th	Centenary chimney from the ceramic industry, Spain	20.8	n. d.	Jimenez et al. (2000)

n. d. = not determined

elements. Therefore, environmental actions and deterioration might have influenced the results obtained. The values range from 6.7 to 21.8 MPa and exhibit a very high coefficient of variation (up to 60%). Most studies indicate low values for compressive strength and a large dispersion of the values, with coefficients of variation ranging between 25 and 55%; but unusual strengths, higher than 50 MPa, were reported by Pauri et al. (1994).

The large variability of historical clay bricks is evident in several cases. As an example, in the 15th century Episcopal Palace of Pienza, Barbi et al. (2002) found an average value of about 26.9 MPa; while Bati and Ranocchiai (1994) reported strengths between 21.7 and 51.4 MPa, though a large majority of bricks exhibited compressive strengths between 20 and 30 MPa. A second example is given in two studies by Baronio and Binda (1985, 1986), who analysed the bricks from the Church of S. Lorenzo in Milan (3rd–4th centuries). An average compressive strength of 12.5–27.5 MPa and 34.5 MPa respectively, was found.

3.3.2.2 Modulus of Elasticity

The modulus of elasticity is frequently found in the literature and is also characterized by large variability (Table 3.2). Significant differences have even been found between values proceeding from distinct studies of the same monument, which confirm the difficulty in defining this parameter. Moreover, it is not always clear how authors measured the values presented, even if most standards refer the use of the linear part of the stress–strain curve in a range of 30–50% of the maximum stress value. The values found range from 1 to 18 GPa, which represents a range between 125 and 1,400 f_c, where f_c is the compressive strength. Most common values are in the range of 200 f_c, with an average value of 350 f_c.

3.3.2.3 Tensile Strength

In the presence of tensile stresses, clay bricks behave similarly to other quasi-brittle materials such as concrete or stone. After microcracking and maximum load are reached, post-peak behaviour is characterized by the progressive decrease of the tensile strength due to localization of deformation at a single crack. Tensile strength is very low when compared to compressive strength, being often neglected. Tensile strength depends mostly on the strength of mineral grains and of the matrix that binds them. Additionally, there is some dependence on the chemical composition, inclusions and the amount and dimension of pores. Because the strength depends heavily on the weaker zones, homogeneous raw clay with little impurities provides higher tensile strength.

Tensile strength is frequently reported as a percentage of the respective compressive strength, usually between 3% and 10%, and sometimes up to 13.5%. Binda et al. (2000b) reported tensile strengths between 0.1 and 2.6 MPa for the bricks of the bell-tower of the Cathedral of Cremona, Italy, which represent 1% and 10% of the respective compressive strengths. Baronio and Binda (1986) found a tensile strength of 5.5 MPa, which corresponds to 5–6.5% of the respective compressive strengths. It is noted that the tensile strength is rather dependent on the test set-up (Van Mier 1984). Flexural tensile strength is frequently confused with the true uniaxial tensile strength measured by a direct test, and often results in tensile strengths much higher than the real values.

3.3.3 Chemistry of Clay Bricks

3.3.3.1 General Composition

Raw clay can be characterized by means of chemical and mineralogical studies (Moropoulou et al. 1993; Cultrone et al. 2004; Pauri et al. 1994). These are frequent in archaeology for characterizing old ceramics and pottery, and in the characterization of old mortar properties (Barrios et al. 2000; Binda et al. 2000a). The determination of the chemical composition of old bricks allows the identification of possible deficiencies that occurred during their production, like the presence of organic matter, lime nodules, harmful soluble salts and other impurities that might influence the durability of the brick (Robinson and Borchelt 1994). Soluble salts and other impurities are one of the most important factors of brick decay and are frequently found in old clay brick fabrics (Baronio et al. 1985; Brocken and Nijland 2004). Chemical composition can also provide information about firing temperature and degree of vitrification (Cultrone et al. 2000), which is relevant for the manufacturing of new replacement bricks (Elert et al. 2003; Cardiano et al. 2004; López-Arce et al. 2003). Finally, chemical composition can explain, to a certain extent, the brick colour by indicating the presence of colorants and other additives.

Chemical oxides commonly found in clay bricks are the following: silica (SiO_2), alumina (Al_2O_3), iron (Fe_2O_3) or ferrous oxide (Fe_3O_4), potassium oxide (K_2O), titanium dioxide (TiO_2) as well as sodium (Na_2O), calcium (CaO) and magnesium (MgO) oxides. Silica and alumina constitute the base elements of clay and are usually found in the following proportions: about 50% for SiO_2 and 15–20% for Al_2O_3. Other components might be considered like barium (Ba), zirconium (Zr), strontium (Sr), rubidium (Rb) and manganese (Mn). However, these elements are always present in very small quantities and expressed in parts per million (ppm), while the proportion of the main components is expressed in percentage of the material volume.

Figure 3.2 reports the proportion of the main chemical constituents of clay bricks from the 12th to 18th centuries, with proportions of silica in the range of 53–61% and alumina in the range of 22–32% (Fernandes 2006). The variability of these constituents is rather low, suggesting that the raw clay material is similar in most bricks. The oxides CaO, Na_2O, Fe_2O_3 and TiO_2 exhibit a significant dispersion. The presence of the first two components is usually due to the contamination by lime mortars and food preparation, respectively; while the remaining oxides are natural colorants of clay bricks, giving a characteristic reddish and yellowish colouring if present in small quantities, respectively. In particular, a low amount of Fe_2O_3 provides a light colour for the bricks.

Chemical composition can differ substantially in old bricks, with reports of clay bricks from the 12th to 13th centuries showing 38% of silica, 21.5% of alumina and 32.5% of ferrous oxide (López-Arce et al. 2003). Also, Moropoulou et al. (1993) reported the chemical composition of clay bricks from the Basilica of Hagia Sophia, which exhibits a much higher proportion of silica (30–70%) and a lower proportion of alumina (8–16%) than normal clay bricks.

3.3.3.2 Provenance Determination

Chemical composition can provide an estimation of the provenance of the clay (Capedri and Venturelli 2005), making it possible to manufacture replacement bricks with the highest possible compatibility with the existing ones. For this task,

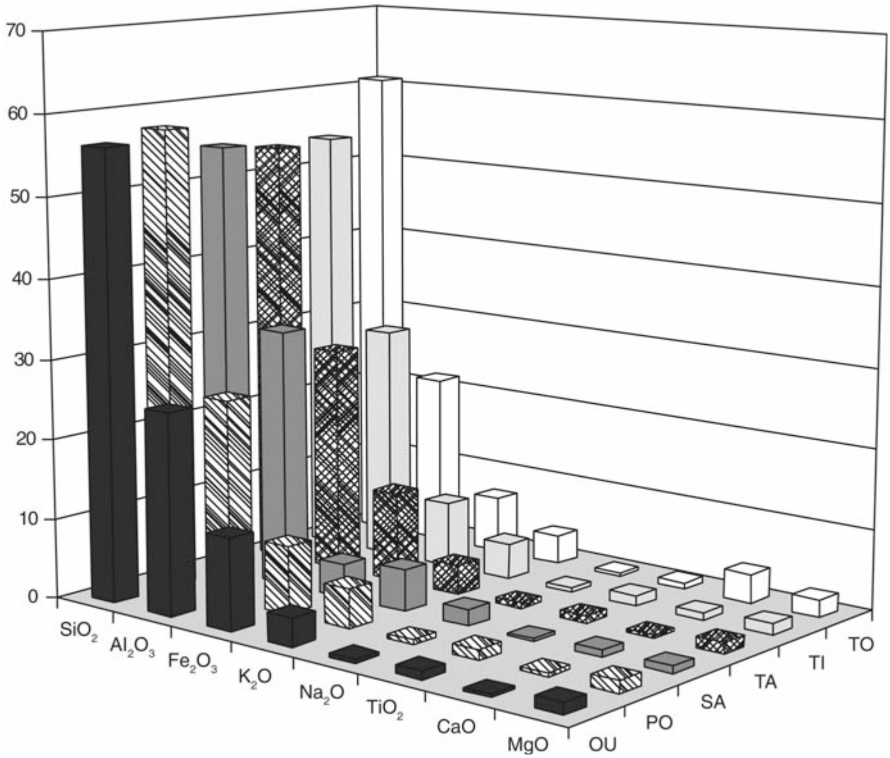

Fig. 3.2 Average proportion of the principal chemical components of old clay bricks

brick samples can be analysed using a statistical methodology described in Castro (1999), based on the comparison between the Euclidean distances of the 'chemical composition' vectors between different groups.

Specimens can be grouped according to their chemical similarity, being the groups characterized by the average values and respective standard deviation for the various determined chemical elements. The analysis of the bricks in Fernandes (2006) revealed that most bricks are similar within each provenance and that the component SiO_2, which is the largest component in clays, contributes very little to the distinction between old samples and cannot be used to distinguish any particular characteristic of bricks. Besides, no single component was found to strongly influence a particular group of bricks, meaning that bricks characterization is influenced by all chemical constituents. Moreover, in certain cases, bricks that are territorially very close exhibit different chemical characteristics. In this case, the period of manufacture and the evolution of the clay treatment and production process produced such results.

The brick groups found were compared with groups present in a database containing the chemical constituents of archaeological and ethnographical ceramics coming from diverse places in Portugal (Castro 1999). At this very large level of database comparison, it was found that the bricks from Tibães and Pombeiro

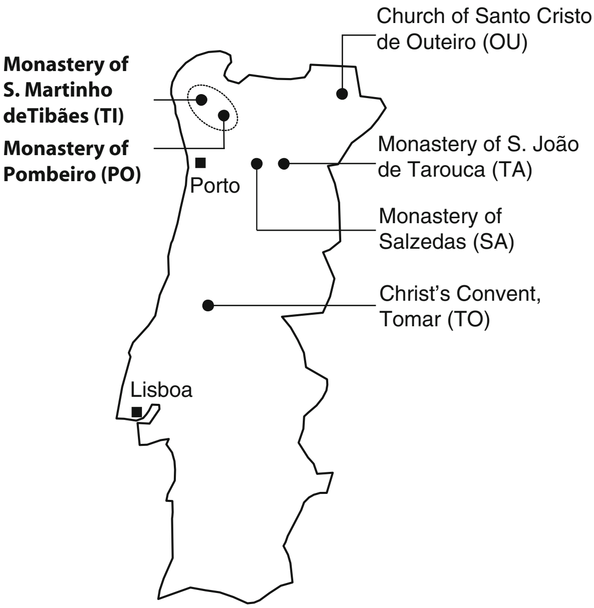

Fig. 3.3 Map showing the location of the monuments where the bricks where gathered

monasteries exhibit a strong similarity and present the typical composition of clays from ethnographical ceramic samples found in the same area (Fig. 3.3). For the remaining groups, it was not possible to determine any type of correspondence, suggesting that archaeological ceramics cannot be compared with old building bricks.

3.4 Drilling Resistance

3.4.1 Description of the Technique

Mechanical characterization of old materials is fundamental to adequately diagnose the conservation state of monuments; and for this purpose destructive tests in laboratories and on site inspections provide valuable information. However, material sampling and destructive tests should be limited in cultural heritage buildings. In order to overcome this constraint, different non-destructive testing methods have been developed as an attempt to obtain the necessary results without causing damage to the structure. Several tests allow one to obtain qualitative results, especially those based on wave propagation, unfortunately with poor correlation with mechanical properties. Impact techniques, such as the Schmidt hammer, do not provide data on the in-depth strength variation. Minor-destructive tests (MDT) provide reliable results related to internal cohesion and mechanical properties.

Special equipment, the drilling resistance measurement system (DRMS), was adopted by Fernandes and Lourenço (2007) to measure, continuously and reliably, the superficial resistance and in-depth cohesion properties of old clay bricks. Further information about technical and scientific backgrounds can be found in Exadaktylos et al. (2000). The DRMS, originally developed to determine the effectiveness of the treatments based on consolidants (Tiano 2001; Tiano et al. 2000a), was adapted to obtaining data that could be correlated with the compressive strength of old clay bricks.

The DRMS enables the user to obtain the drilling resistance based on the measurement of the force (in Newton, N) and torque (in mN m) necessary to drill a hole under specific operative conditions: diameter, penetration rate (*PR*), rotational speed (*RS*) and depth. The prototype used in the experiments and illustrated in Fig. 3.4 was provided by SINT Technology, and consists of the followings components: (i) a mechanical device equipped with positioning and drilling engines as well as force and torque load cells, with 100 N and 100 mN m of maximum capacity, respectively; (ii) an electronic unit that contains the power unit, control boards for DC and stepper engines, signal amplifiers for load cells, computers for test procedure, graphic visualization and data storage; (iii) a tripod; two steel plates with three threaded bars and lock nuts to hold specimens for laboratory testing, three adjustable sharp-pointed bolts to provide the support during in situ tests over regular and irregular surfaces.

3.4.2 Experiment

A set of bricks from the 12th to 18th centuries taken from six monasteries in Portugal was drilled in a laboratory environment; and the drilling resistance, DR_σ, of each unit was obtained. For microdrilling measurements, the specimens were fixed between the steel plates of the special equipment part, with a zero stress state. The test parameters are essentially material dependent and low penetration rates and rotational speeds increase the returned thrust and torque (Tiano et al. 2000b).

Old clay bricks are mainly made of soft material (clay mass). The presence of hard and highly abrasive sand grains and stone fragments requires an adequate choice of values for *PR* and *RS,* considering the low resistance of the clay mass and the high resistance of harder elements. From preliminary experiments, the system parameters were fixed to: $PR = 10$ mm min^{-1} and $RS = 600$ RPM. In typical old masonry elements, the brick units are laid down in the direction of the bed surface and the only visible and accessible surfaces are the ones in the bed plane. So, drilling was carried out in the accessible surfaces, preferentially located in the central area of the specimen in order to avoid any possible edge effects.

The value used to characterize the microdrilling resistance, DR_σ, is the drilling force divided by the cross-section of the drill bit. The presence of high strength inclusions such as sand grains or stone fragments inside the brick specimens, and the presence of voids and cracks, severely affects the average drilling resistance of bricks just in the same way they can influence the compressive strength. However, the contribution of these local defects in the behaviour of the whole brick is less relevant.

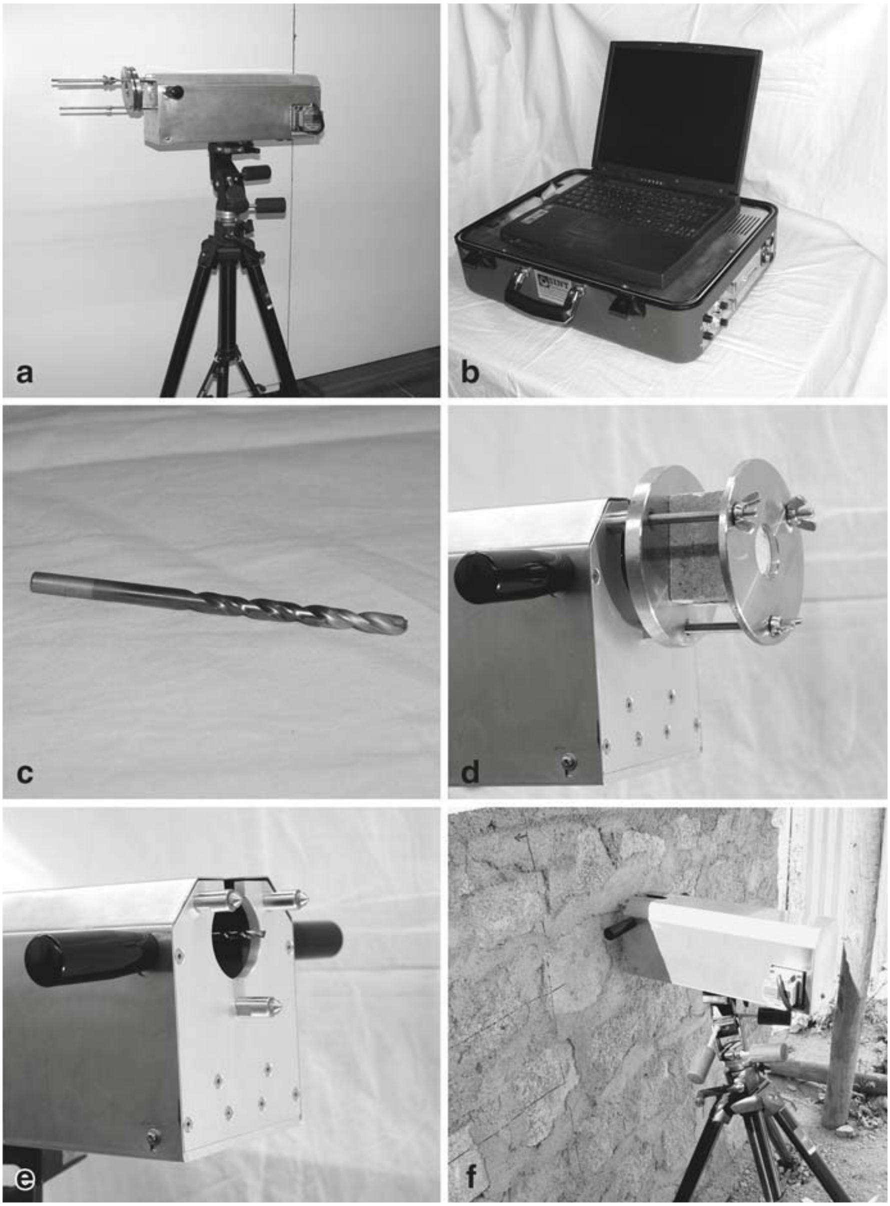

Fig. 3.4 Equipment and operation possibilities of the DRMS equipment: **a** mechanical device in tripod with drilling engine, **b** control unit with data visualization and storage unit, **c** special DIABER (Italy) drill bit, **d** sample ready for testing, in the steel plates clamping system and **e** view of the three adjustable sharp-pointed screws for **f** in situ usage of the equipment

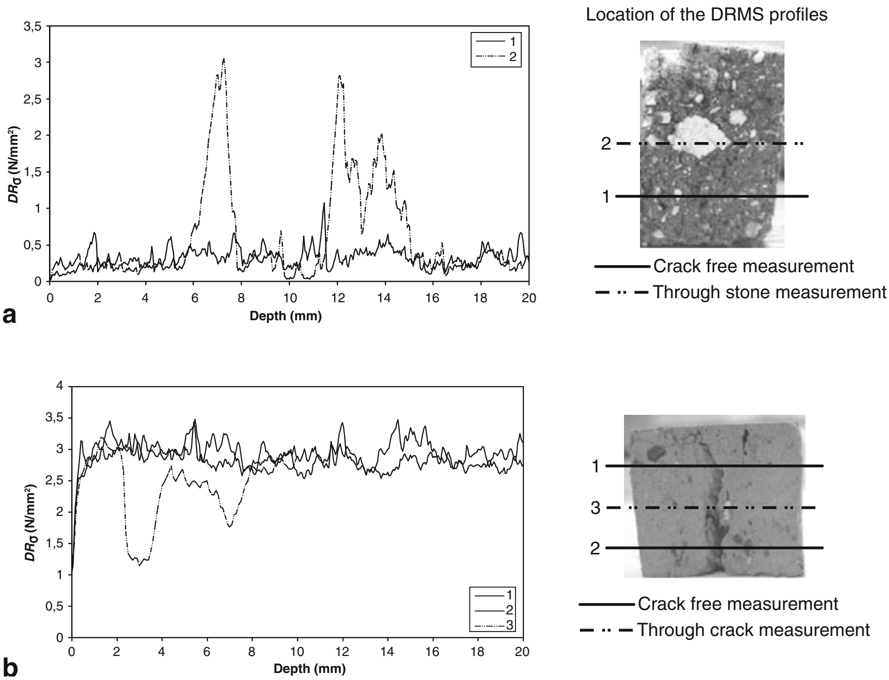

Fig. 3.5 Example of the drilling resistance measurement when crossing **a** a stone fragment and **b** an internal crack

Figure 3.5 illustrates the result of drilling through a stone fragment and through a crack in the interior of the brick. In both cases, rather homogeneous resistance profiles with moderate irregularities, due to the microstructure of brick, are observed (in black) together with one profile showing the influence of the anomalies previously described (in grey). As a result, the average drilling resistance of the profile that crossed the stone fragment is 80% higher than the average of the remaining profiles; while in the case of the profile crossing an internal crack, the drilling resistance decreased 20% relatively to the other ones.

In this case, three to five holes were carried out in each specimen, taking into account its size and difference between consecutive measurements. Low strength dips and high strength peaks were systematically removed. As an example, Fig. 3.6 shows the portion of data removed from the profile as well as the data used to calculate the average drilling resistance.

3.4.3 Correlation of Drilling Resistance and Compressive Strength

The values for the drilling resistance of old clay bricks DR_σ range from 0.83 to 3.19 N mm^{-2}. In order to obtain mechanical data without sampling, a model had

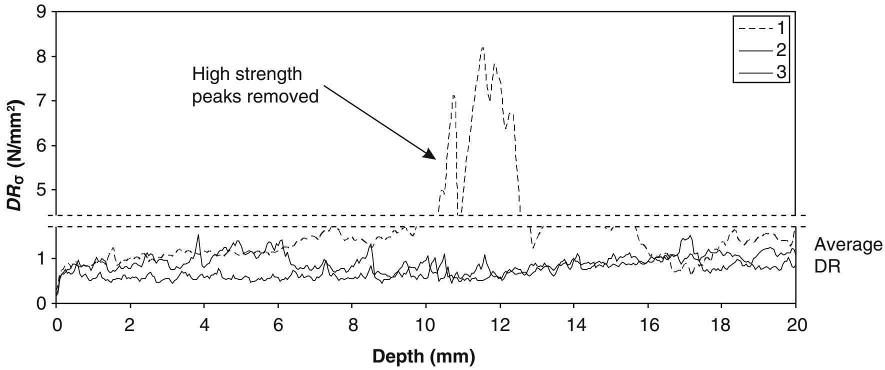

Fig. 3.6 Example of the calculation of the average DR_σ of specimen TO15

to be made to indirectly obtain mechanical data from drilling resistance data. The graph illustrated in Fig. 3.7 shows that the relation between the drilling resistance and the compressive strength of the clay brick exhibits a similar trend, which confirms the existence of a possible relationship between these two properties. Note that here only the average values for each set are shown, and not the full results.

The complete results of all test specimens regarding the correlation between drilling resistance and compressive strength are shown in Fig. 3.8. A non-linear fit was computed with a power curve using: $f_c = 9.196\ DR_\sigma^{0.609}$, which provided a R^2 of 0.74. This result is in line with other studies that proposed a power law to correlate the compressive strength of old clay bricks from ultrasonic velocity and Schmidt hammer rebound tests (Kirka and Erdem 2005). The regression line is shown over the complete dataset in Fig. 3.8, being applicable also for modern traditionally

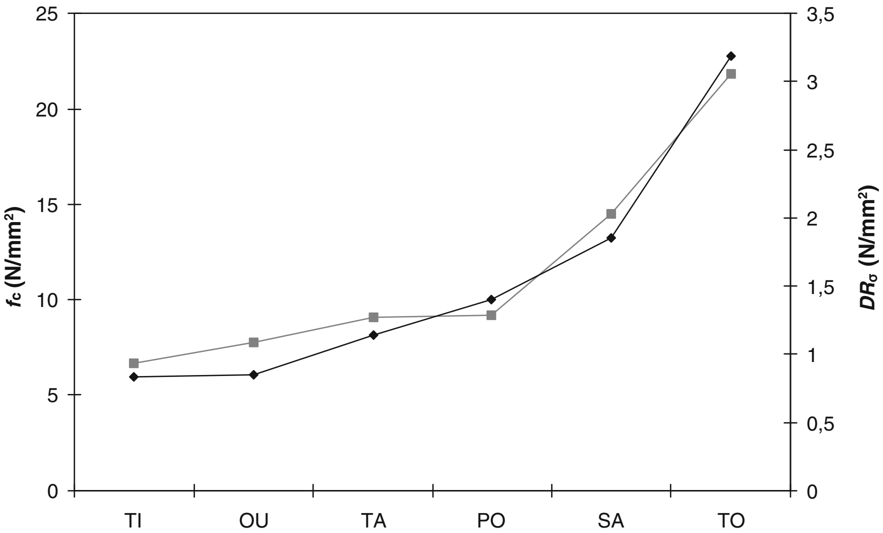

Fig. 3.7 Comparison between drilling resistance and compressive strength of old bricks

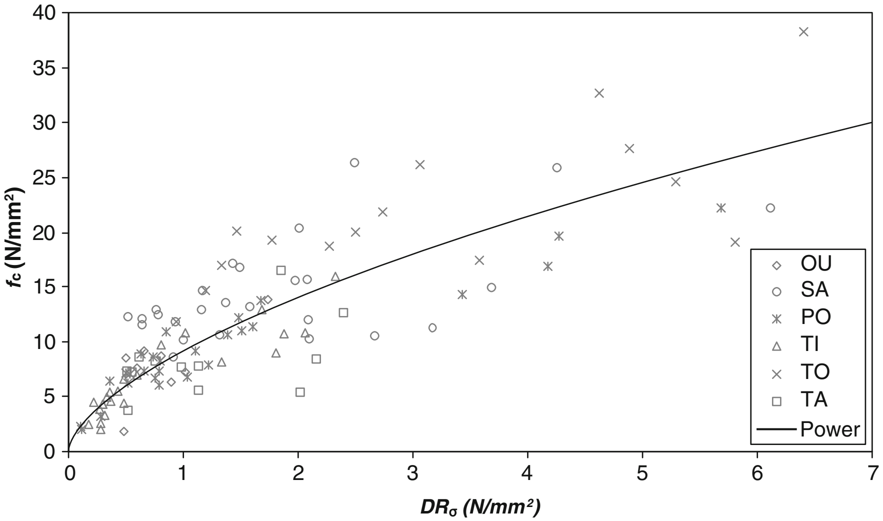

Fig. 3.8 Linear and non-linear correlations between compressive strength f_c and drilling resistance stress DR_σ for the entire sample

handmade fired clay bricks (Fernandes and Lourenço 2007). The reason for the wide scatter is that old bricks have no uniform properties and DRMS is a local measure, much influenced by cracks and inclusions.

3.5 Conclusions

Old clay bricks are difficult to characterize, due to the wide diversity of raw materials, manufacturing processes and conservation states. The physical, mechanical and chemical properties of historical clay brick exhibit a large spectrum and a significant variability. The literature survey and the authors' tests indicate a high porosity (15–40 vol.%) and water absorption (10–20 vol.%). The suction can be rather high (up to 0.35 g cm^{-2} min^{-1}), while the apparent density is low (1,500–1,800 kg m^{-3}). The compressive strength shows a huge scattering with values mostly ranging from 1.5 to 30 MPa. No trends could be found regarding age or origin, as the amount of data is limited.

In general, raw clays used in old clay bricks seem to have some consistency with respect to the proportion of the main chemical constituents; while bricks of the same origin generally exhibit a strong chemical similarity. It is also noted that clay bricks have a chemical composition different from the ceramic products of archaeological remains since no similarities with available archaeological data have been found.

Finally, it was shown that a minor-destructive test (microdrilling) allows adequate assessment of the compressive strength of old clay bricks, using appropriate correlations.

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Chapter 4
The Mỹ Sơn Temples in Vietnam: Construction Techniques and Structural Issues

Paola Condoleo

4.1 Introduction

The monumental area of Mỹ Sơn, whose actual name means "beautiful mountain", was located in the ancient and blooming Amarāvatī, one of the five provinces in the kingdom of the Cham population, who dwelled in central Vietnam from the 2nd century. In the beginning their reign was known as Lin Ly; only after the 6th century did it become the Champa reign (Vickery 2005). Nowadays Mỹ Sơn extends over almost 15 ha in the Quảng Nam province (central Vietnam), approximately 50 km south-west from the city of Dà Nẵng. The archeological area is located in a small valley surrounded by a semicircular chain of low mountains, from which mount Hòn Châu rises, also named *Răng Mèo* ("the cat's tooth") by the local population for its peculiar shape (Fig. 4.1).

Between the 4th and the 13th century, the Cham people built more than 70 brick masonry buildings in this area. Thirty of them, gathered in 8 religious Hindu complexes (usually referred to as "groups"), are still recognizable nowadays. As a matter of fact, only in rare cases was the principal temple an isolated building: a religious complex consisted generally of a sanctuary with several annexes.

These several monuments are not to be considered as single entities, but as parts of a larger project, which is the result of a precise plan. Starting from the selection of the area, which was carefully prepared by the ancient architects (*Sthapati*) on the basis of its geotechnical characteristics, the building process was carried out following rituals and symbolic rules established by the Brahmin (*Sthāpaka*) (Kramrisch 1946). The monuments not only represented an act of devotion, but also had to be regarded as an expression of power, since they were built by a commission of people from the royal class.

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Fig. 4.1 Mỹ Sơn: view of group C with the Răng Mèo in the background

Champa history is characterized by several conflicts and wars that often exposed their territories to pillage and destruction. Mỹ Sơn was certainly not spared, as it was often the theater of depredations and plunderings, whose signs are still visible today.

The continuous pressure of the people from Đại Việt, which forced the Cham to leave their territories (14th century) and then reduced them to a minority (18th century), took turns with the powerful Khmer neighbors, looking for new commercial harbors. After the conquest by Đại Việt of the Vijaya (another province where the political power had moved) in the 14th century, the site of Mỹ Sơn was pillaged several times, and abandoned to nature: the rapid growth of a thick forest, that made its way inside the structures, was the cause of the damage and partial destruction of some of the buildings.

The discovery of the site dates back to 1885, when the French (who were present in Vietnam since 1850) had the complete control of the country, though the local dynasties maintained a purely formal reign. A squad of French soldiers, during the patrol of the forest covering the buildings, was astonished at the sight of the impressive ruins and numerous statues, which recalled the style of the just discovered area of Angkor, in Cambodia. The first studies of the area started in 1899, with the work of Louis Finot, Director of the EFEO (École Française d'Extrême-Orient); his work was then continued in 1901, when the studies and researches in the architectural and historical–artistic field by Henri Parmentier, chief architect of the EFEO, began:

he catalogued every group with a letter (from A to N) and every building with a number, with the intent of making the studies easier (Parmentier and Finot 1904).

The war of independence marked a natural stop to the research work: in 1956 France left Vietnam, which shortly afterwards became the theater of another long and bloody conflict. During the Vietnam War, in 1969, the buildings which had till then survived the ravages of time were severely bombed and many were razed to the ground; other buildings were indirectly damaged by the vibrations and the shell fragments.

The first restoration works on some damaged buildings were carried out from 1982 to 1986 by a Vietnamese–Polish team led by Hoang Dao Kinh and Kasimierz Kwiatkowski (Kwiatkowski 1985, 1990).

The area of Mỹ Sơn was inscribed officially in the World Heritage List in 1999.

The fundamentals of the present work were developed in the framework of a tripartite preservation project, started in 2000 on group G. It involved Politecnico di Milano (Department of Structural Engineering—DIS and Lerici Foundation), the Vietnam Ministry for Cultural Heritage and UNESCO, and was supported by the Italian Ministry of Foreign Affairs.

The research was oriented to the buildings of group G because they show peculiar and homogeneous characteristics, both in terms of architecture and from an artistic point of view. Moreover, since it was built in the decadence period of the Cham civilization (following the opinion of French scholars), it was never restored. Only at the beginning of the 20th century was it subjected to the excavation intervention by Arch. Henri Parmentier, which cleared the area from the dumps, performed a survey, and collected part of the decorative materials. Another important characteristic of group G (and of other monumental groups of Mỹ Sơn) is the peculiar masonry technique, with bricks of different shapes connected by very thin joints of organic material.

During the intervention it was possible to carry out direct observations, and subsequent accurate verifications through on-site and laboratory testing. The knowledge gained on several aspects (materials properties and construction techniques) was instrumental for later developments, mainly aimed at understanding the structural behavior.

4.2 General Description of the Temples

The principal temple, named *Kalan* (Fig. 4.2), is located inside the sacred area. It contains the cell where the divinity was guarded: the only person entitled to enter the cell was the Brahmin. Invariably located south of the *Kalan* is the *Kośa Gṛha*, where the sacred texts and objects used during the religious ceremonies were gathered. The sacred area is delimited by a sort of wall enclosure (*Antaramandala*): access was only possible through a monumental entrance, *Gopura*, whose shape resembles that of the principal temple on a smaller scale. This building consists of two opposite gates: the first faces the entrance to the *Kalan;* the second one is

Fig. 4.2 View of the principal temple (*Kalan*) with a portion of the wall enclosure (*Antaramandala*) of group G

placed at the entrance of a main hall, *Mandapa*. This hall, usually located outside the sacred area, was used to gather pilgrims: inside, they could prepare the offerings for the divinity and pray. Outside the sacred area was also an annex building, *Pôsha*, with entrances on all sides, used to guard the founding memorial stone.

Not all the groups have the same orientation: generally they lie on the East–West axis, and they all face the current course of the river.

4.3 Characterization of the Building Materials

To understand the principles of the construction technique a thorough characterization of the building materials, whose properties influence the building process, was carried out by means of laboratory tests, on-site investigations, archaeological excavations, direct observations, and accurate photographic and geometrical surveys.

One of the most characteristic features of the buildings of Mỹ Sơn that emerged during the survey is the presence of very thin joints: the bricks are so tightly bonded, that the joints are hardly visible (Fig. 4.3a, b). It is well known that a reduction of the joint dimension is beneficial for the mechanical properties of masonry, but a technological limit to this reduction is posed by the use of traditional mortar, due to the aggregates dimensions. This observation makes it clear that a different material had to be used by the Cham for the thin joints found in the masonry.

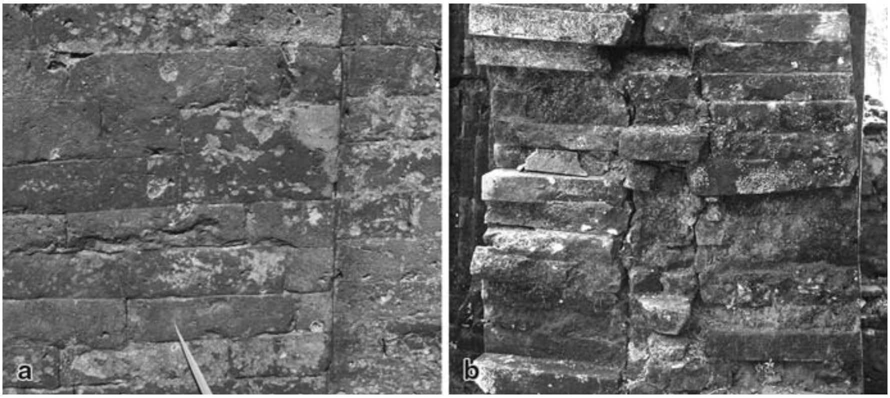

Fig. 4.3 Masonry of the Mỹ Sơn temples: **a** thin-joint masonry in prospect; **b** vertical section of the wall of the principal body (G1)

The first part of the project was devoted to investigating the properties of this material: to this purpose, a series of experimental campaigns has been carried out at the Department of Structural Engineering—DIS of the Politecnico di Milano, under the direction of Prof. Luigia Binda, since 2000 (Ballio et al. 2001). Several chemical, physical, and mechanical tests were carried out on samples taken directly on site. In the following, reference will be made only to the test results which have a direct consequence on the structural behavior and, more specifically, that can be directly related to the construction techniques. A complete description of the test results can be found in Condoleo (2007).

4.3.1 Bricks

Petrographic observations on thin sections, microscopical examination with polarized light, and X-ray diffraction (XRD) were carried out on brick fragments (Liborio and Crespi 2002). In some bricks, fragments of fired materials (*chamotte*) were found: this testifies to the use by the Cham of waste material for brick formation. Another important finding concerns the firing temperature, which was determined from XRD to be certainly below 850°C (Liborio 2005): this issue has significant consequences on the mechanical behaviour of the bricks, even though the exact modalities of the firing process together with the kilns used should be further investigated.

Measurements on complete bricks and on small cubes (40 mm) cut from the bricks were carried out according to European standards. The results exhibit slight heterogeneities, but some values of general validity can be assumed: bulk density = 1655 kg m^{-3}, water absorption coefficient = 160 g m^{-2} $s^{-1/2}$, water absorption by total immersion = 18–24%.

The density is slightly lower than that of the bricks commonly used in Europe; as a matter of fact, the latter values of the absorption testify to medium-high porosity and thus a lighter structure of the brick.

Uniaxial compression and indirect tensile tests (by splitting) were carried out on the brick specimens. The compression tests were carried out also on small specimens (100 × 100 × 100 mm), obtained by cutting two bricks still joined by the original material (couplets), as well as on triplets of brick cubes (i.e., three superimposed brick cubes), in order to determine the modulus of elasticity and the Poisson's ratio (Binda et al. 2006).

The values obtained from the tests on the small cubes ranged from 15 to 17 MPa: the scatter is rather low, thus indicating a rather homogeneous material. The compression tests carried out on a pair of joined bricks were compared with those obtained on non-joined bricks. The strength of non-joined bricks (11.5 MPa) is lower than that obtained on the joined pair (12.6 MPa), indicating the advantage due to the presence of the thin joints when well bonded to the bricks.

The modulus of elasticity was calculated as the slope of the stress–strain curves between 30 and 60% of the peak load. In the same tests the transverse strain was measured and thus the Poisson's coefficient was calculated as the ratio between the transverse dilation and the longitudinal contraction. The values of the elastic modulus are close to 1.4 GPa, while the Poisson's ratio is approximately 0.1. These values refer to the brick couplets with joints consisting of organic material; it is reasonable to assume that brick couplets with mortar joints would exhibit lower values of stiffness, because of the higher value of the deformations localized in the joint.

4.3.2 Joints

The aim of the laboratory analyses was to ascertain whether the materials used in the Mỹ Sơn temples are fully related to natural products offered in the area and manufactured by local people. In more detail, an open question was whether the organic materials were obtained from the resins of the trees growing in the area surrounding Mỹ Sơn (and belonging to the species of the *Dipterocarpaceae*). Two types of analysis were carried out: a Thin Layer Chromatography (TLC) and a spectrochemical analysis (Binda et al. 2008).

From the TLC it was found that the resin used for the external joints contained a high percentage of *Dammarenediol*, a component which is commonly present in the family of the *Dipterocarpaceae*.

The second analysis allowed a comparison between the original joint material and an organic resin still used nowadays in Vietnam mainly to caulk boats, the *Daù Raì*, which is obtained from the *Dipterocarpus alatus*. The results show that they are rather similar; slight differences are probably due to oxidative processes which might have occurred in the joints during the centuries.

Summing up, it is reasonable to assume that the organic material used for the external joints comes from the *Dipterocarpus alatus*.

As for the material used in the internal joints, the petrographic observations on thin section, and the microscopical examination with polarized light made it clear that it consists mainly of clay, chamotte and quartzitic temper. This finding allows us to assume that this composite is a sort of mortar (without lime), which was explicitly conceived for the masonry (Liborio 2005).

4.4 Construction Techniques

The on-site observations and the survey process made it possible to identify features common to all the buildings.

All the monuments in the Mỹ Sơn area are characterized by four fundamental parts: the foundations, the base, the central body and the roof. The internal floor plan is always located at the end of the base (cymatium); access was made possible by stairs, generally made of stone, with the exception of the *Pôsha*, which, in keeping with its function, had no access.

4.4.1 Use of Masonry in the Different Parts of the Buildings

The foundations, which were accurately investigated in group G and building E7, were mainly shallow, with a thickness varying from 15 to 30 cm, while their width was close to that of the masonry. Underneath, a preparation layer made of sand mixed with soil and occasionally with ceramics was found. It seems that after preparing the site on which the complex would be built, the lines limiting (externally and internally) the plan of the foundation walls were traced (Fig. 4.4). It is reasonable to assume that, because of its importance, the principal temple was traced first.

The limited depth of the foundations may be justified by the presence of the underlying bedrock, representing a solid and stable ground. Actually the same technique was used in the case of E7, where the ground is mainly constituted by silty materials: this fact allows us to consider this technique as a typical feature of Cham architecture and not just peculiar to the investigated groups. This hypothesis could be strengthened by performing further excavations in the zones without rocky ground.

The foundations consist mainly of half bricks (rarely whole bricks), with an irregular layout, and a filling of clay (rarely admixed with rubbles) and ceramic fragments.

The other three parts (base, central body, and roof) of the buildings generally consist of masonry of fired bricks with thin joints. Stones were used almost exclusively for lintels, opening frames and decorative elements, with the exception of temple B1, which had a base completely made of stone.

The masonry in elevation is composed of three leaves (see Fig. 4.3b). The two external leaves consist of entire bricks with very thin (micrometric) joints of natural

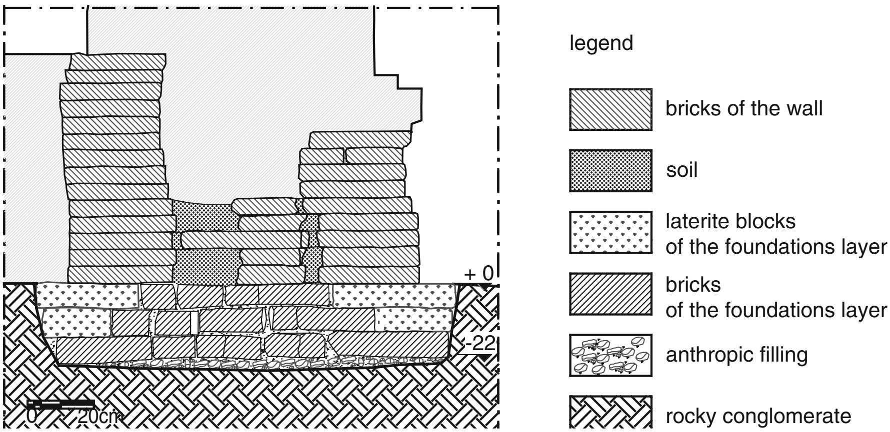

Fig. 4.4 Sketch of the foundations of G3: section on the south side of G3 at the level of the footing

resin. It is noteworthy that this technique enhances the protection of the walls from biological attack by vegetation, provided the joints are not damaged.

The dimension of the internal leaf, as well as the type of filling, varies with the maximum dimension of the masonry: unlike the external leaves, which are homogeneous along the height of the temple, the internal leaf has different characteristics from the base to the principal body. The filling of the base is mainly homogeneous, and made up of entire or half bricks, put in place in an orderly way and joined together by clayey soil; in some buildings, a filling consisting of rubble, sand, brick fragments, and soil can be found. In the principal body, the internal leaf consists of entire or half bricks, joined together by clayey soil.

The external leaf consists of horizontal and continuous layers of headers. Only in a few cases are stretchers found, to provide some toothing between the leaves. The layers of headers are offset by only a few centimeters: this circumstance implies a weak toothing between adjacent leaves and does not ensure an adequate monolithicity of the masonry, whose behavior tends to be similar to that of three independent leaves.

The roofs vary considerably from one building to the other, and differ mainly for the adopted construction technique: most of the buildings had corbelled vaults; others probably had timber double-pitch roofs covered with tiles, although no examples are left.

4.4.2 *The Scratching Technique*

The bricks of the external leaves were put in place using the scratching technique, which consisted of placing the bricks and then scratching the two adjacent surfaces in the horizontal plane, one against the other (Fig. 4.5). The most proper use of the

Fig. 4.5 Typical scratching process on a brick

scratching technique for the construction of the masonry requires enough space for the horizontal movement (from the external surface of the leaf to the internal one): thus it is reasonable to assume that the two external leaves were built prior to the internal one, in order to have enough clear space between them. Moreover, the use of this peculiar technique is favored if the bricks are scratched parallel to their length: in this way, a more uniform distribution of the pressure is possible and the process becomes easier for the workmanship.

It was Parmentier (1918) who made the first hypothesis about the scratching technique: nevertheless, he later (1948) changed his mind on this specific aspect. Both in situ observations and laboratory investigations confirm that his first guess was correct. It is possible to notice parallel scratches on the surfaces of the bricks (Fig. 4.6a), in most cases aligned with their length. These scratches could also be caused by the forming process, as assumed in previous studies on the subject (Claeys 1934): however, a thorough observation makes it possible to see that the scratches on adjacent surfaces fit perfectly together (Fig. 4.6b). Therefore, they had to be produced during the mutual movement along adjacent surfaces by small quartz particles present in the material and trapped between the bricks. The scratching process, performed in a very accurate way and for a sufficiently long time, was favored by the low firing temperature of the bricks ($T \approx 800°C$), which led to the production of a highly porous and thus "softer" material (see Sect. 4.3.1, and Binda et al. 2006), and was carried out without wetting the surfaces: this is confirmed by the presence of bricks which are really clamped together (Fig. 4.7a). In some cases, the consumption of the bricks due to the scratching led to

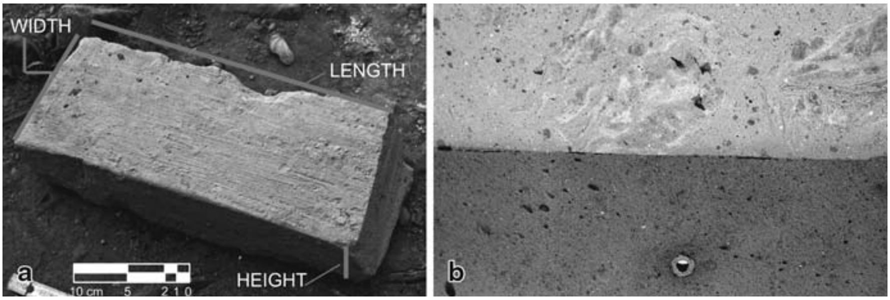

Fig. 4.6 **a** Brick with evident parallel scratches on its surface; **b** a couple of cut joined bricks

a misalignment of the horizontal courses: to overcome this side effect, the brick courses were doubled where needed, by inserting rows of bricks with variable thickness (Fig. 4.7b).

The main reason for the use of the scratching technique is to be found in the use of natural resin, instead of mortar, for the joints. The resin was laid only after the scratching process, on the two perfectly-corresponding surfaces of the bricks. Parmentier (1948) formed the hypothesis that the resin was laid prior to the scratching process, to serve as a lubricant, but this seems to be at odds with the results of some tests performed on site and in the laboratory (Fig. 4.8), where, on the contrary, it was ascertained that the resin prevents the sliding movement of two superposed bricks. The fact that the scratched surfaces perfectly fit together made it possible to obtain thinner layers of resin, to the advantage of its adhesive power: laboratory tests have shown that, due to its low permeability, the resin can dry adequately only if its thickness is low (Binda et al. 2007). In this way the stiffness and strength of the brick-joint assembly are increased, as confirmed by the laboratory tests (see Sect. 4.3.1), to the advantage of the structural behavior of the masonry (Binda et al. 2006). In general, in the presence of mortar joints, the strength of the brick-joint assembly increases systematically, with the reduction of the joint thickness, provided the latter is not reduced to zero (Binda et al. 2005). In this case, a strength

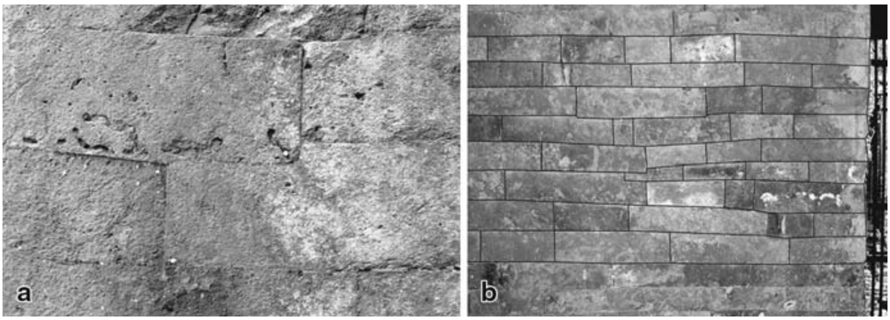

Fig. 4.7 **a** Individuation of bricks clamped together inside the masonry: internal north side of G1; **b** examples of doubled courses to redefine the horizontality of the alignments: internal west side of D2

Fig. 4.8 Preparation of the specimens by scratching before laying the resin

reduction is observed, probably because of the stress concentrations ensuing from the superficial irregularities of the bricks. The scratching technique allows this side effect to be largely overcome, thanks to the attainment of two complementary surfaces, perfectly clamped together.

The resulting thin joints are an advantage also in terms of the overall durability of the masonry, reducing the penetration of aggressive biological components: an example of local damage in the joint and of its detrimental effects is shown in Fig. 4.9, where the penetration of roots inside the masonry can be noticed. These disadvantages would be even greater in cases where mortar were used for the joints. Thus, it was also mandatory that the masonry should be as homogeneous as possible, without any point of weakness.

With regard to this aspect, the scratching technique itself could also be the source of some problems. Since the process of scratching was rather time-consuming, it is reasonable to assume that the temples were built by many teams of workers that were active simultaneously. The most likely sequence of the building process was that two (or more) teams started building a single masonry simultaneously from two adjacent corners of the building, and then proceeded towards the center, meeting in the middle: this hypothesis seems to be confirmed by the fact that the corner areas

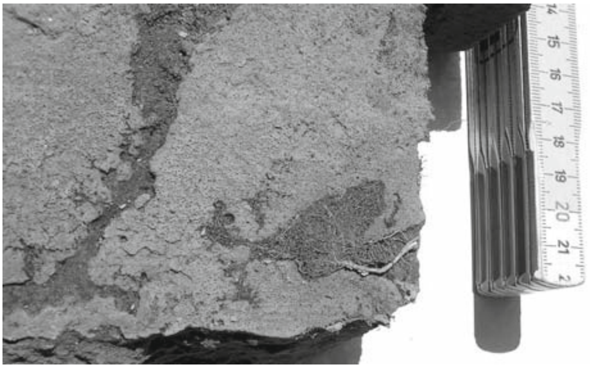

Fig. 4.9 Penetration of roots inside a severely-damaged joint

are usually regular, exhibiting a sound alternation between headers and stretchers, and a good overall toothing: on the contrary, in the areas between the corners, the systematic use of randomly-located bricks of special shape can be observed. These bricks were probably put in place to fill the voids between opposite-advancing teams at the meeting point: these voids were due to the inevitable uncertainties in the placement of the bricks, which were increased by the scratching technique and the ensuing casual reduction of the dimensions of the bricks (Condoleo 2007). The fact that the number of special bricks inside a given course is variable testifies that the teams of workers simultaneously active on a masonry were generally more than two. The special bricks are different in shape and dimensions; they were probably carved by means of chisels, after the firing process: therefore, no special formworks were used. A common feature is the presence of inclined faces (Fig. 4.10), having a variable angle with respect to the horizontal (45–60°). As a matter of fact, inclined faces are instrumental in favoring the consumption of the bricks by means of scratching, and thus a proper closure of the resulting sub-vertical joints. If a brick is inserted between two bricks with vertical faces, it is impossible to scratch it properly; this procedure becomes easier, if the faces are inclined, as confirmed by the observations carried out during the preservation project (Condoleo 2007).

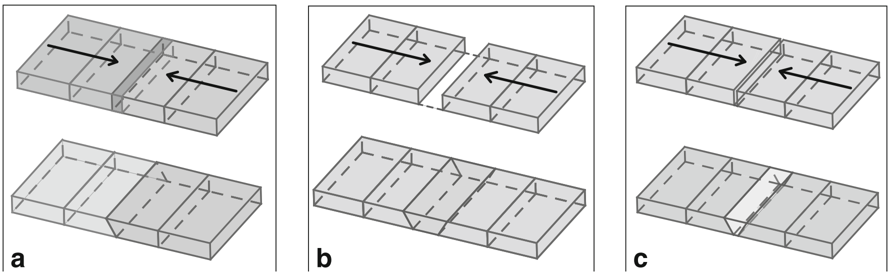

Fig. 4.10 Ideal schemes used to interpret the residual space between two opposite fronts advancing during the building process of the wall: **a** opposed bricks with corresponding and complementary inclined faces; **b** bricks with inclined mirror faces and a trapezoidal brick in between, used to fill the gap; **c** bricks with inclined mirror faces and a triangular brick in between, used to fill the gap

Fig. 4.11 Evened surface on the north side of G1 (picture taken with oblique light)

For the above-mentioned reasons, the scratching technique makes the construction of a regular wall difficult: this circumstance was overcome by the Cham by carving and smoothing the external surfaces of the masonry until the desired shape was obtained (Fig. 4.11). This process resembles the typical work of a sculptor, and is somewhat unusual, considering that it was carried out on brick buildings. More common examples thereof can be found in the case of stone buildings, for instance in Indian architecture.

4.4.3 The Toothing

The above-mentioned characteristics of the building process make it clear that the resin could be used only on a single layer of bricks, because enough space was needed for the scratching technique: therefore, resin was used only on the external leaves, whose thickness is constant and equal to the length of the bricks. The thickness of the internal leaf, on the contrary, is variable and mostly related to the overall dimension of the building. The exclusive use of headers in the external leaves led to an offset between the outer and inner leaves being reduced to a few centimeters (or in some cases totally absent) and, consequently, to a weak toothing between the external leaves and the internal one (see Fig. 4.4). This circumstance has a consequence on the structural behavior of the masonry: the three leaves tend to behave independently, and the masonry is not monolithic. In a few cases stretchers were used: however, the fact that the length of the bricks (≈ 29 cm) is approximately twice their width (≈ 17 cm) leads also in this case to a reduced offset in the vertical direction. Another attempt to improve the toothing was the use of half bricks, but this was rarely applied and proved to be inadequate. The most proper procedure to guarantee the toothing consists of connecting the external leaves to the internal one by means of bricks with complementary inclined faces, with a "sawtooth" profile (Fig. 4.12). This connection has the same structural function as the traditional indentation with vertical joint offset: it prevents vertical relative displacements along the interface, by means of compressive contact stresses on the horizontal faces of the saw. However, when compared to the usual toothing achieved by a horizontal offset, it is more efficient: the transfer of compressive stresses across the horizontal faces is ensured on every course, making the connection almost continuous. In a traditional toothing, on the contrary, the active horizontal faces are located on every other course, and the resulting connection is slightly more discontinuous.

Fig. 4.12 Toothing external and internal leaf by means of bricks with inclined faces (north-west corner of the G1 basement)

The presence of "sawtooth" profiles is evident in the basement and, in a few cases, also in the central body: the great number of bricks with inclined faces found during the archeological excavations suggests that the same expedient was used also in the elevation. However, if this procedure had been applied systematically throughout the whole structure, the damage and collapse due to air movements caused by bombs and shells could perhaps have been reduced.

4.5 Numerical Model of the Toothing

The beneficial effects of the afore-mentioned characteristic arrangement concerning the toothing were quantitatively studied by means of a FE model.

Geometrically, the model represents a vertical section of the three leaves, with a height of 1 m, a thickness of 0.30 m for the external leaves and 0.20 for the internal one. All the analyses were carried out with triangular or quadrilateral linear elastic 2D elements. The materials properties were taken from the laboratory tests (see Sect. 4.3.1) carried out on the brick-joint assemblies coming from the external leaves (bricks bonded by thin resin layers); for the internal leaf (bricks with clay joints, chamotte and quartzitic temper) an elastic modulus lower than that of the outer leaf ($\approx -30\%$) was assumed to account for the higher deformability of the mortar layers. The values of density, elastic modulus and Poisson's ratio are given in Table 4.1. Since the section is meant to represent a zone in the middle portion of the wall (i.e., far from the corners of the building, from openings and other geometrical irregularities), the 2D elements used in the analyses are in a state of plane strain.

The boundary conditions at the base of the model are represented by rollers in the horizontal and vertical directions: this type of restraint was chosen to simulate contact with the soil, as well as the horizontal restraint guaranteed on the vertical faces of the foundations by the adjacent ground, and on the base by the friction against the ground.

Two different load conditions were considered, namely the self-weight of the wall and a horizontal force applied on the top. The self-weight depends on the value of the density, which is the same for the three leaves, while the horizontal force was given a unit value. These two conditions can be regarded as a simplified representation of typical vertical and horizontal loads.

Since the model represents only a part of the wall, the results give no information on the absolute values of the stresses; however, they allow some conclusions to be drawn on the effects of the different toothing levels on the stiffness of the wall and also on the stress distribution.

Two limit conditions for the toothing between the leaves (Models A and B) and a situation which can be regarded as a good approximation of the real behavior

Table 4.1 Physical and mechanical characteristics used for the FE models

Leaf	Density (kg m^{-3})	Elastic modulus (GPa)	Poisson's ratio
Central	1655	1.0	0.10
External	1655	1.4	0.10

(Model C) were represented: the differences concern the geometry of the interfaces between the inner and the outer leaves, and the constraints enforced along these interfaces. The number of degrees of freedom in the three models is the same. Going into more detail:

Model A: the interfaces are smooth; no shear is transferred across the interface, only compressive stresses can be transmitted by frictionless contact; this model represents the absence of toothing, and the three leaves basically behave independently.

Model B: the interfaces are smooth and perfectly tied to each other, i.e., normal and shear stresses are transmitted: this assumption represents a perfect bonding between the leaves that behave as if they were a monolithic body.

Model C: the interfaces are shaped following a sawtooth profile: the interaction between the leaves is enforced, also in this case, by means of a frictionless contact restraint. For the self-weight of the wall, since the central leaf has a lower stiffness, the compressive stresses are transmitted, without any friction, only on the inclined faces of the teeth. In the case of the horizontal force applied at the top of the wall from the left to the right, at the interface between the left leaf and the central leaf the transmission of the horizontal stresses is guaranteed by the inclined faces; the shear connection, on the contrary, is ensured by compressive stresses on the horizontal faces of the teeth. At the interface between the central and the right leaf, the contact and the ensuing normal stresses are active only on the inclined faces.

Figure 4.13 shows the deformed shapes due to the self-weight for the three models. It is possible to notice that in the first case (Fig. 4.13a), due to the lower value of its stiffness (represented by the elastic modulus), the central leaf undergoes larger displacements in the vertical direction. In the second case (Fig. 4.13b), the displacements are reduced by the beneficial effect of the shear transmitted at the interfaces between the leaves, thanks to the perfect bonding. The real situation (Fig. 4.13c) falls in between the two previous cases: there is still a lack of compliance in the vertical displacement at the top of the wall, but the average displacement is reduced with respect to the absence of bonding. Moreover, it is worth noting that the outer

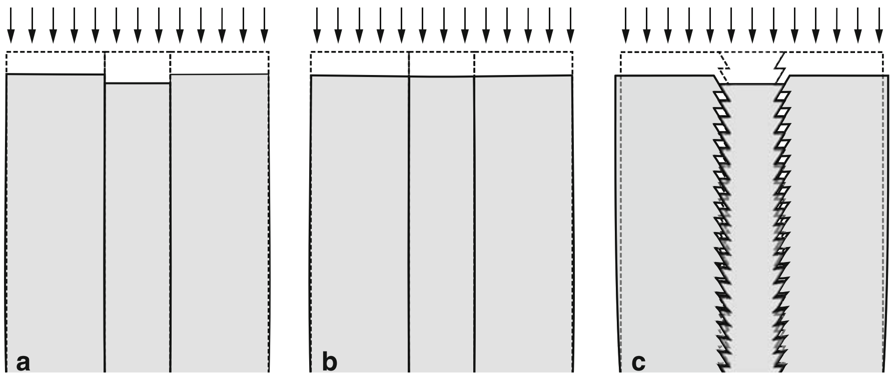

Fig. 4.13 Shape deformed by the self-weight for the three FE models considered: **a** Model A: any bonding; **b** Model B: with perfect bonding; **c** Model C: with the sawtooth profile between adjacent leaves

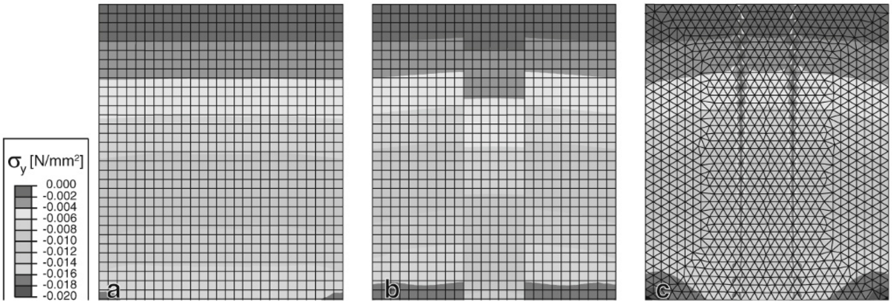

Fig. 4.14 Vertical normal stresses due to the self-weight for the three FE models considered: **a** Model A: any bonding; **b** Model B: with perfect bonding; **c** Model C: with the sawtooth profile between adjacent leaves

leaves exhibit an outwards displacement, due to the wedging action exerted by the inclined faces of the teeth: there is a sort of dilatancy, a phenomenon which is common in soil and rock mechanics.

Figure 4.14 shows the distribution of the vertical normal stresses. In Model A (Fig. 4.14a) the three leaves behave as three independent columns and therefore the value of stress increases linearly along the height of the wall, with the value at the bottom depending only on the height of the wall and the density of the material (which are the same for all leaves). In Model B (Fig. 4.14b) a decisive role is played again by the supporting action exerted by the outer leaves, which results in a stress relief of the central leaf. Of course this stress relief brings in an increase of the stress level in the outer leaves, as expected from equilibrium considerations. Finally, Model C (Fig. 4.14c) exhibits a stress contour which is in some way intermediate between the previous models.

Figure 4.15 shows the deformed shapes of the three models subjected to a horizontal force at the top left corner. In Model A (Fig. 4.15a), the three leaves behave like three cantilevers: along the interfaces there is a sliding movement, and no shear is transmitted. In Model B (Fig. 4.15b), the wall assembly behaves as a unique cantilever, the stiffness is greatly enhanced and the displacement at the top is signifi-

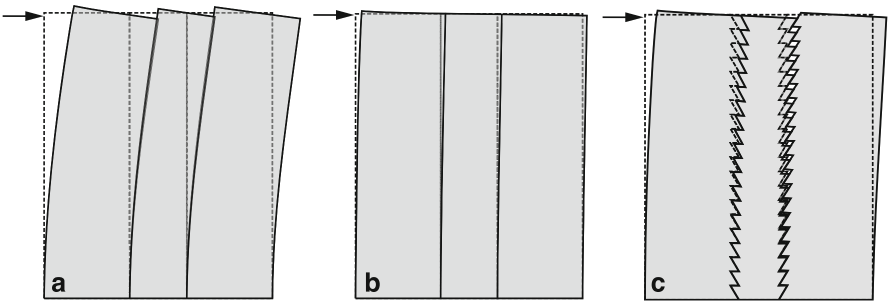

Fig. 4.15 Deformed shape caused by a horizontal force on the top left corner for the three FE models considered: **a** Model A: any bonding; **b** Model B: with perfect bonding; **c** Model C: with the sawtooth profile between adjacent leaves

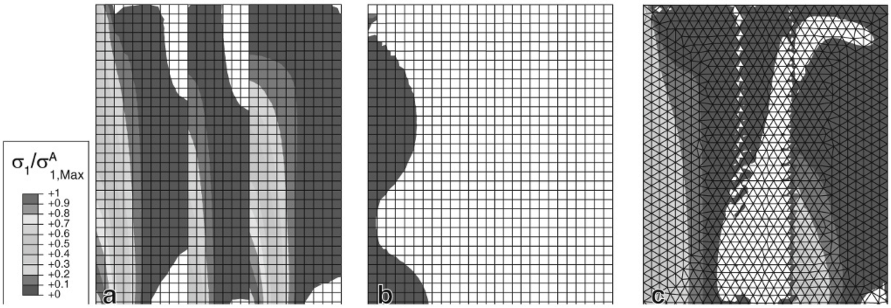

Fig. 4.16 Maximum principal stresses (normalized with reference to the maximum value measured in Model A) due to the horizontal force on the top left corner for the three FE models considered: **a** Model A: any bonding; **b** Model B: with perfect bonding; **c** Model C: with the sawtooth profile between adjacent leaves

cantly reduced. In Model C (Fig. 4.15c) sliding occurs only at the interface between the central and the right leaf, whereas at the interface between the left leaf and the central one it is prevented by the presence of the horizontal faces of the teeth. The stiffness increases and the displacement is close to that of Model B. It is worth noting that the effectiveness of the interlocking connection at the interface between the left and the central leaf brings in a reduction of the force transmitted to the right leaf. This reduction would be even greater if the thickness of the central leaf were to be increased.

The effects of the different assumptions on the stresses caused by the unit horizontal force are shown in Fig. 4.16, where the maximum (tensile) principal stresses are normalized with respect to the highest value obtained in Model A (Fig. 4.16a): this ratio gives significant indications regarding the effect of the interaction between the leaves on the stress distribution. Fig. 14.16c shows that in the case of Model C, there is a strong reduction in the maximum tensile stresses thanks to the toothing and thus to the enhanced monolithicity of the wall assembly: moreover, the extension of the zones subjected to tensile stresses is definitely reduced.

4.6 Conclusions

It is evident that Cham people conceived their buildings as a unique body, beginning with a rather approximate "sketch" of its general shape, and then working, by means of the various above-mentioned techniques, to the attainment of the final shape. This approach is applied also to the smallest parts of the building (i.e., the bricks), where the attainment of the best shape according to the requirements of the structure is obtained by means of a sort of modeling process, which is the scratching technique. This modeling process was made possible by the low firing temperature of the bricks that resulted in a "softer" material.

Although the use of organic components as building materials is common practice in South-East Asia, in the case of Mỹ Sơn the resin used for the joints brings in great advantages in terms of durability, preventing biological attack, which is a key design parameter, considering that the area is completely surrounded by the jungle. However, the fact that the resin cannot be used for the internal leaves implies a reduction of the monolithicity of the masonry, with the three leaves behaving as independent bodies. Providing the bricks with inclined faces, creating a "sawtooth" profile, allows this problem to be overcome, as demonstrated by means of the FE models presented in Sect. 4.5: Model C, where the geometrical shape of the sawtooth profile was explicitly introduced, shows the effectiveness of this type of toothing, resulting in an increase of the stiffness of the whole masonry, to the advantage of its overall structural behavior with respect to vertical loads.

Of course, a good toothing is beneficial also in the case of horizontal loads: with regards to this aspect, the Mỹ Sơn area is not at high risk of seismicity (ground acceleration = 0.2–0.4 m s^{-2}), but it is fair to say that the historical information about past earthquakes is lacking. Nevertheless, during the Vietnam War the buildings were subjected to significant transverse loads, mainly due to the air movement caused by bombs and shells: it is reasonable to assume that greater damage would have been produced, if no toothing at all had been provided.

The investigations were principally focused on the buildings of Mỹ Sơn and particularly Group G. The question whether other Cham buildings are characterized by the same general features is still an open issue, which surely deserves further investigation, possibly in connection with archeological excavations.

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Part II
Natural Stone

Chapter 5
The White and Coloured Marbles of the Roman Theatre of *Copia* (Cosenza, Italy)

Lorenzo Lazzarini, Silvana Luppino and Carmelo G. Malacrino

5.1 Introduction

There are few existing examples of detailed studies on the use of marble in the decoration of ancient monuments and on the archaeometric analysis performed to establish their provenance. The aim of this paper is to gather the archaeological evidence from a defined context, examine all the different material classes and identify the marble species found in the excavation. We have chosen for this study one of the most important areas of the ancient town of *Copia*, namely the *insula* of the theatre. This area was excavated in the second half of the last century, but it still remains unpublished regarding most of the historical and archaeological aspects. Finally in order to place our results in a wider archaeological context we have also considered some marbles used in other monuments of the town.

5.1.1 Sybaris-Thuricopia: Three Ancient Cities and the Insula of the Theatre

Sybaris was one of the most important Western Greek cities, situated on the Ionian coast of the modern region of Calabria (Fig. 5.1). It was founded during the second half of the 8th century B.C. by Achaean people coming from Peloponnesos. The literary sources refer to the fact that the *oikistes* (founder) was a citizen of *Helike*, but we know that mingled with the Achaean emigrants there were also a number of Troezenian citizens. The *polis* rose rapidly to great prosperity, owing in the first instance to the fertility of the plain on which it was situated. After a short time *Sybaris* extended its dominion across the peninsula with the foundation of various

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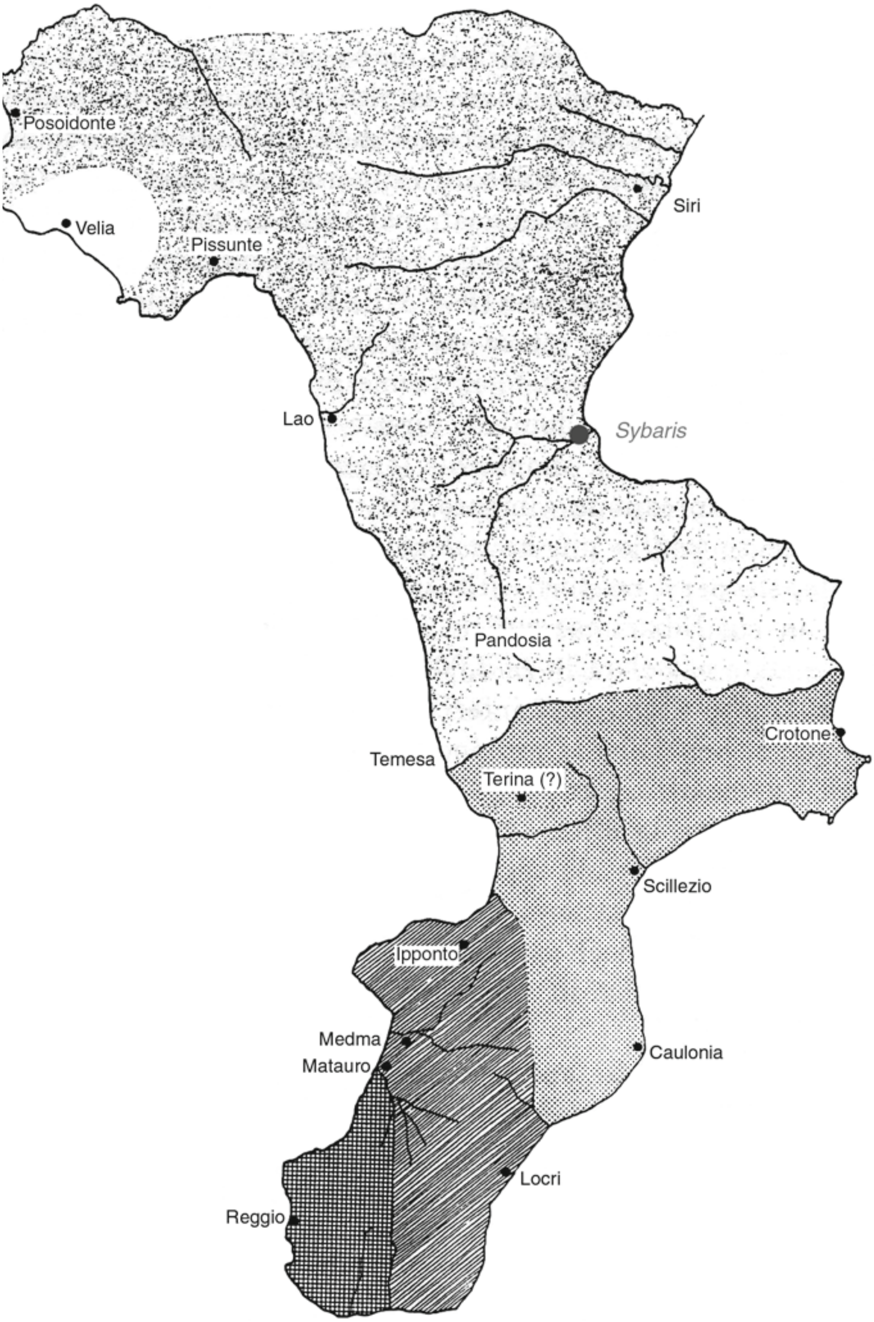

Fig. 5.1 Location of *Sybaris* in South Italy and the extent of its empire. From *Sibari e la Sibaritide* 1993

colonies (*Poseidonia*, *Laos* and *Skydros*). In 510 B.C. the city was destroyed by the citizens of *Kroton* and part of the population moved, particularly to the Tyrrhenian coast. Nearly 70 years later, in 443 B.C. (or in 446 B.C.) the Athenians founded another city on the same area, *Thurii* (so named for the presence of the spring *Thuria*). It soon became a true metropolis, planned by Hippodamos of *Miletus*. The town flourished for two centuries and in 194 B.C. it was refounded by Romans with the name of *Copia* ('abundance' in Latin).

The *insula* of the theatre (Figs. 5.2 and 5.3) is situated at the centre of the town, at the crossing of the two main *plateiai* and near the agorà. It shows a complex stratification of building phases, going from the Archaic Greek period to Late Roman times (Arslan 1970; Guzzo 1993; Paoletti 1994; Malacrino in press).

5.1.2 From the Archaic Period to the Hellenistic Age

Inside the *insula* the remains connected to the Archaic city of *Sybaris* are very limited (Carando 1999). They comprise, excluding pottery and other archaeological materials, a segment of wall (width 1.50 m) built with large stones, found in 1969 in the *postscaenium* area (Bedini 1970).

Fig. 5.2 East view of the *insula* of the theatre of *Copia*

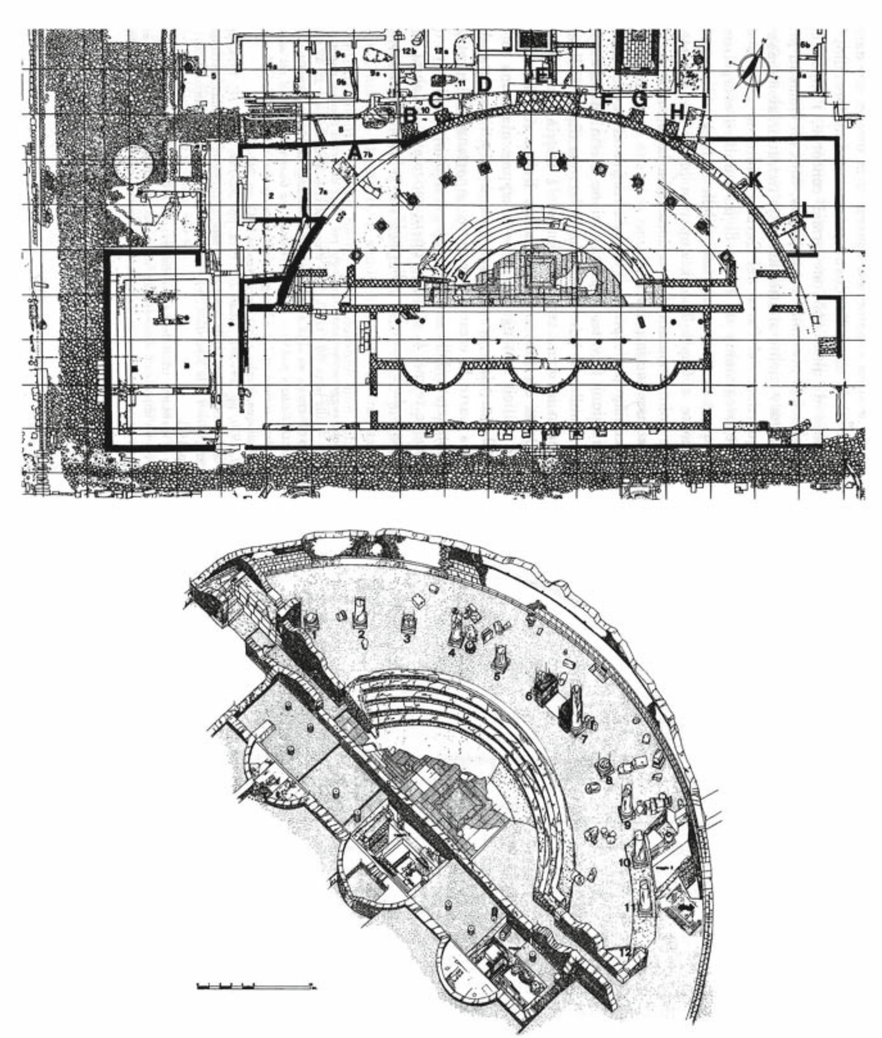

Fig. 5.3 Plan of the *insula* of the theatre (*above*), and axonometric view of the same (*below*)

We also know very little about the occupation of the *insula* after the foundation of *Thurii* in 443 B.C. An important aspect is the shape of the plot occupied by the *porticus* during the Roman period, because part of its sides maintained the position fixed by Hippodamos of Miletus in the planning of the city with *plateiai* and *stenopoi* (Greco 1999a). This refers in particular to the north and east sides, corresponding to the position of two *stenopoi*, and to the west side, which runs along the original outer line of the north-south *plateia*—maybe the *Olympias plateia* cited by Diodorus Siculus (XII, 10, 6–7) (Lapini 1997; Greco 1999b). It was only in the southern section that the *insula* widened its boundaries during the Roman age, spreading to part of the east-west *plateia*—possibly identifiable with the *Thuria* *plateia*—towards the square in front of it, probably in the direction of the Roman forum and the previous Greek agorà (Greco and Luppino 1999). Among the structures detected through the test-pits in the *insula* there is a well (diameter 0.90 m) lined with a layer of pebbles and a squared reinforcement consisting of squared wooden beams (Guzzo 1970).

5.1.3 The Domus from the Late Republic

After the establishment of the Latin colony of *Copia* in 194 B.C. (Paoletti 1993) the *insula* was occupied by private houses. Excavations have unearthed sections of these houses, whose structures have been dated to the beginning of the 1st century B.C. (Guzzo 1998). They include several rooms with walls made of whole and broken pebbles held together by mortar. Some of these spaces had a concrete flooring, often featuring frames and panels decorated with stone *tesserae*. Unfortunately the lack of data and the only partial investigation of the late Republican layers of the *insula* do not allow us to draw the plan of these houses. Their owners were likely to have been extremely wealthy, as can be deduced by their central position within the town, the floor decoration and the wall frescoes.

5.1.4 The Porticus

During the Augustean period the *insula* underwent major transformations. The whole area was reorganized, clearly by a powerful local man. A large semicircular *porticus* (with a diameter of around 62.60 m) was built, flanked in the northern section by rooms following the Hyppodamean boundaries of the *insula*. Towards the east–west *plateia* the area was terraced with a structure in *opus reticulatum*, spreading over part of the ancient *plateia*. The *insula* thus reached dimensions of around 67.50×33 m.

The *porticus* consisted of a monumental edifice, whose layout has been only recently clarified through the excavations carried out in 2007 within a more general restoration project of all the structures of the site (Malacrino in press).

The *porticus* opened onto the east–west *plateia* with its rectilinear side, which was probably enclosed by a wall with a single great axial entrance. The building expanded towards the inside with a porch held by 12 columns, over 6 m wide. Most likely the rhythm of the colonnade was broken at the axis of the edifice due to the presence of a wider span, which reproduced the width of the southern entrance. From the end of this rectilinear porch runs the curvilinear section of the edifice, which expanded with a porch of 16 columns (plus the two corner columns). Several bases and the lower drums of the column shafts have been preserved. These elements were extremely simple: the bases, in sandstone and micro-conglomerate, featured a lower *plinthos* surmounted by a smooth *torus*, a fillet and a deep cavetto; the drums, in local coarsely-porous limestone, were smooth. Two other bases were reused at a later stage in the building of walls. The absence of any lintel belonging to the roof of the *porticus* seems to imply that at least part of the pediment was made of wood. The two central columns were joined to two great pilasters in *opus testaceum*, in order to render the composition more monumental and maybe to support some kind of decorative *fastigium*.

The *porticus* was flanked in the north section by some rooms, as may be inferred from the space of the plot. These structures were built in *opus reticulatum*, in some cases polychrome.

The edifice copiously reused material from previous buildings, from the Archaic to the Hellenistic age (Mertens 1972, 1993). The whole lower section of the semicircular outer wall was built with blocks of local white limestone taken from a structure belonging to the 6th century B.C. Some of the stones, reworked to fit the new use in the *porticus*, showed mouldings and architectural decorations, as well as mason marks and *anathyroseis*.

From the stamps found in the excavation, we can deduce that the roof of the building was made of tiles and covertiles produced in the *figlina* of *L. Vinuleius Brocchus*, where the slave *Cleandrida* worked. The same *L. Vinuleius Brocchus* is mentioned in a marble inscription found, reused, in the decoration of the theatre, and the value appears in another limestone block inscription found directly behind the theatre (Zumbo 2006). *L. Vinuleius Brocchus* was an important local magistrate having censorial powers to which we can ascribe the construction or the restoration of the *porticus*.

The *porticus* was damaged by a fire in the second half of the 1st century A.D. The subsequent restoration involved not only the outer walls, but also the inner columns, whose shafts were reinforced with metal hoops.

5.1.5 The Theatre

In the first half of the 2nd century A.D. the whole area witnessed a new, important building project. The layout of the *porticus* was very well suited to the shape of the cavea of a small theatre. It was defined by the previous circular wall, which was filled in and reinforced with the later addition of several external buttresses. The layout of the *porticus* and more generally of the *insula* resulted in a longitudinal contraction in the plan of the theatre, with a *cavea* and an *orchestra* far from being semicircular.

Similar to the structural solution adopted in the coeval theatre of Gioiosa Ionica (Ferri 1926), the theatre incorporated a substantial part of the colonnade of the porch into the *cavea*. The new structures of the stage completely erased the southern side of the *porticus*, except for a few bases of some columns, which were left below the flooring of the western *basilica*.

The theatre featured a continuous *cavea*, constructed with a core in *opus caementicium* and a face in *opus testaceum* for the steps (Malacrino 1999). The structure has been completely stripped of the original marble covering and only the first five rows of seats have been preserved. Two small staircases, also in brickwork, run at either end of the *cavea*, touching the *analemmata*. These walls were made in *opus quadratum* with blocks of local white limestone, at least in parts lined with marble slabs, as testified by the holes for the metal rods which kept them in place. The *orchestra* in *opus sectile* was decorated with large marble slabs arranged in a motif of squares. The stage building, lacking the *aulaea*, presented a low *pulpitum* held by the shafts of columns most probably taken from a Hellenistic *stoa*. The *hyposcaenium* was therefore hollow. Access to the *pulpitum* was gained through two side doors, which were connected to the two large *basilicae*. The *frons scaenae* in *opus mixtum* showed the scheme in use during the 2nd century A.D., with three curvilinear *exedrae* which framed the *porta regia* and the *hospitalia*. As in the nearby theatre of *Scolacium* (Malacrino 2005), the *scaena* was decorated with columns and pilasters in coloured marble, as well as with several white marble statues (Faedo 1994). Behind the *scaena* was the *postscaenium*: a long space having two wide lateral openings.

An important phase of transformation probably took place during the 3rd century A.D. The *orchestra* was repaved with large marble slabs, and the three *exedrae* of *the frons scaenae* were also modified. Several buttresses were added, evidently to offset the thrust of the *cavea*. Some scholars (Paoletti 1993) have suggested that during this stage a wooden *cavea* was replaced by one in masonry built on an embankment.

Unfortunately we do not have any data on the last stages of this monument. It is possible that also this area, after being plundered (Guzzo 1998), was abandoned in the 4th–5th centuries A.D., together with the other known parts of the town. Further information might be deduced through the study of the materials belonging to the strata below the ruins of the structure of the edifice.

5.2 Sampling and Experimental

All the statues and inscriptions found in the excavation of the theatre, and a representative number of architectural elements, including fragmentary slabs of *opera sectilia,* were sampled. All samples for analysis were small scales taken by using a hammer and a sharp chisel. The analytical methods used for white and coloured marbles are described below.

5.2.1 White Marbles

All determinations were made on a single fragment of ca. 2×1×0.5 cm for each sample. Part of the sample was finely ground and the powder subjected to isotopic analysis (see below).

The remaining part was used for the preparation of a thin section for mineralogical-petrographic study of the marble under a polarizing microscope.

5.2.1.1 Minero-Petrographic Analyses

The purpose of the microscopic examination of thin sections is to determine the fabric, accessory and secondary minerals, in addition to the calcite and dolomite characteristics which are the principal constituents of all types of marble.

More specifically, the following parameters were determined for the marbles and their structure:

- maximum grain size, a parameter of significant diagnostic importance, as has been shown by recent studies, since it is linked to the metamorphic grade reached by the marble;
- boundary-shapes of the calcite/dolomite grains, also connected to the type of metamorphic event that generated the marble;
- type of structure (homeoblastic = with isodiametric grains, heteroblastic = with grains of various dimensions, then mosaic, polygonal, mortar, etc.), in direct relationship with the type (equilibrium, non-equilibrium, polymetamorphism, etc.) and grade reached by the metamorphism.

For the petrographic description, previous specific studies of ancient marbles (Lazzarini et al. 1980), as well as classical treatises on petrotectonics (Spry 1986) were taken into consideration.

5.2.1.2 Isotopic Analyses

Those samples of dubious identification after petrographic examination were also subjected to isotopic analysis. This was carried out on the carbon dioxide derived from small portions (20–30 mg) of the powdered sample subjected to a chemical attack with 100% phosphoric acid at 25° in a special vacuum line, according to the procedure suggested by McCrea (1950) and Craig (1957). The resulting CO_2 was then analysed by mass spectrometry. The instrument used is endowed with a triple collector and permits the measurement of both isotopic ratios ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) at the same time. The analytical results are conventionally expressed in δ units, in parts per thousand:

$$\delta = \left(\frac{R_{sample}}{R_{std}} - 1 \right) \cdot 1000$$

in which R_{sample} and R_{std} represent the isotopic ratio of oxygen and carbon in the sample and in the reference standard, respectively. The standard adopted is PDB for both oxygen and carbon [the PDB standard is the rostrum of the *Belemnitella americana* of the Cretaceous Pee Dee Formation of South Carolina].

Isotopic characterisation has proved to be very useful in the marble identification of ancient artefacts (Gorgoni et al. 2002). Its use is becoming more and more widespread owing to its notable sensitivity, to the small quantity of material necessary for the analysis, and to the availability of a rapidly growing database (Barbin et al. 1991; Gorgoni et al. 2002) that permits increasingly trustworthy comparisons, especially if the isotopic data are evaluated together with the mineralogical-petrographic results from the same samples, as in the present study.

5.2.2 Coloured Marbles and Stones

Coloured marbles and stones found in the excavations of the theatre were first studied macroscopically and compared with atlases of ancient decorative materials (Mielsch 1985; Gnoli 1988; Borghini 1989; Lazzarini 2004). In case of doubtful identification, or of unknown provenance, small samples were studied by optical microscopy in thin section, and their relative powders by X-ray diffraction. The results were compared with published papers, mostly those collected in the eight volumes of the ASMOSIA's transactions (1988–2009), and in recent specialist handbooks (Lazzarini 2004, 2007).

5.3 Results and Discussion

5.3.1 White Marbles

The artefacts of white marbles were divided into the following groups: statuary (Figs. 5.4 and 5.5), architectural elements (Fig. 5.6), and inscriptions (Fig. 5.7). The results obtained are summarised in Tables 5.1 and 5.2, respectively.

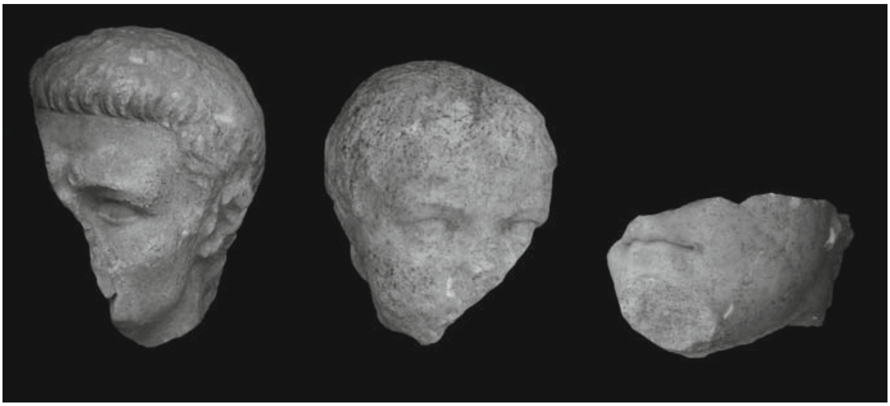

Fig. 5.4 Fragmentary heads of: Claudius, infant, Caligula (from *left* to *right*)

Fig. 5.5 Fragmentary statues of: Nike, seated male, dressed female, male torso (from *left* to *right*)

Most of the statuary proved to have been made of two marbles, the *lychnites* variety of Parian from the area of Stephani, island of Paros (the heads of Claudius, and of the infant, the male seated figure and torso, the female statue), and Pentelic from near Athens (the fragments of the wings, feet and drapery of the statues). Less abundant was *marmor lunense* from Carrara (Italy), used for the head of Caligula, the statue of a Nike, and two different fragments (one calcitic and one also containing some dolomite) of a relief depicting a town, and Parian marble from the open-pit quarries of Lakkoi, not far from Paroikia, the island's capital (Fig. 5.8).

Fig. 5.6 Fragmentary architectural elements from the *insula*: pilaster capital, frame, pilaster decorated with plant motifs, ionic column (*left* to *right*, *top* to *bottom*)

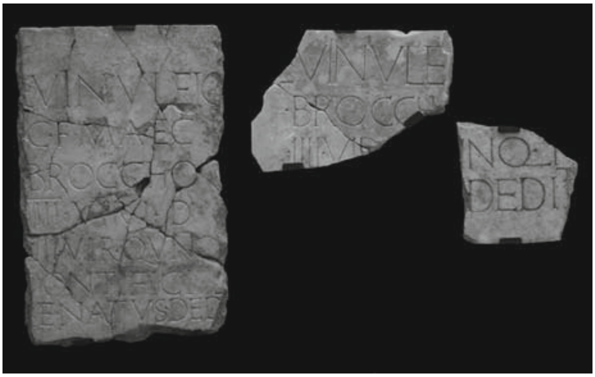

Fig. 5.7 Fragmentary inscriptions of *L. Vinuleius Brocchus*

From these results it may be deduced that rich patrons offered portrait and ornamental statuary made of prestigious marbles for the decoration of the theatre: in particular, the abundant presence of *lychnites*, the most famous marble of antiquity, normally quite rare and used only for very precious artefacts, as well as that of Pentelic marble.

A quite different situation results from the identification of architectural elements and inscriptions. The first, including lintels, columns, capitals, frames and slabs are mostly of Carrara marble, with a single exception for a Corinthian capital of Pentelic marble. Of the second, two inscriptions dedicated by *Brocchus* are of Parian marble from Lakkoi, and one relative to the *Augustales*, is of Carrara marble.

5.3.2 Coloured Marbles

Quite a large quantity of coloured marbles was found in the excavation of the theatre in the form of fragmentary columns, frames, and especially of slabs of different dimensions and thicknesses used for covering floors and facing walls (*opera sectilia*).

From both macroscopic and minero-petrographic studies (limited to granites, rosso antico, and breccias, the only species necessitating laboratory identification, Fig. 5.9) it has been possible to identify the following species, grouped according to their provenance:

Asia Minor (Fig. 5.10): africano (from the ancient town of *Teos*, now Sigacik, province of Izmir), breccia corallina (from the modern village of Vezirhan, province of Bilecik), and pavonazzetto (from ancient *Docimium*, now Iscehisar, province of Afyon).

Greece (Fig. 5.11): breccia di settebasi (from the island of Skyros), verde antico (from Mount Mopsion, province of Larisa), portasanta (from Latomi, near Chios, the main town of the island of Chios), rosso antico (from the Mani peninsula,

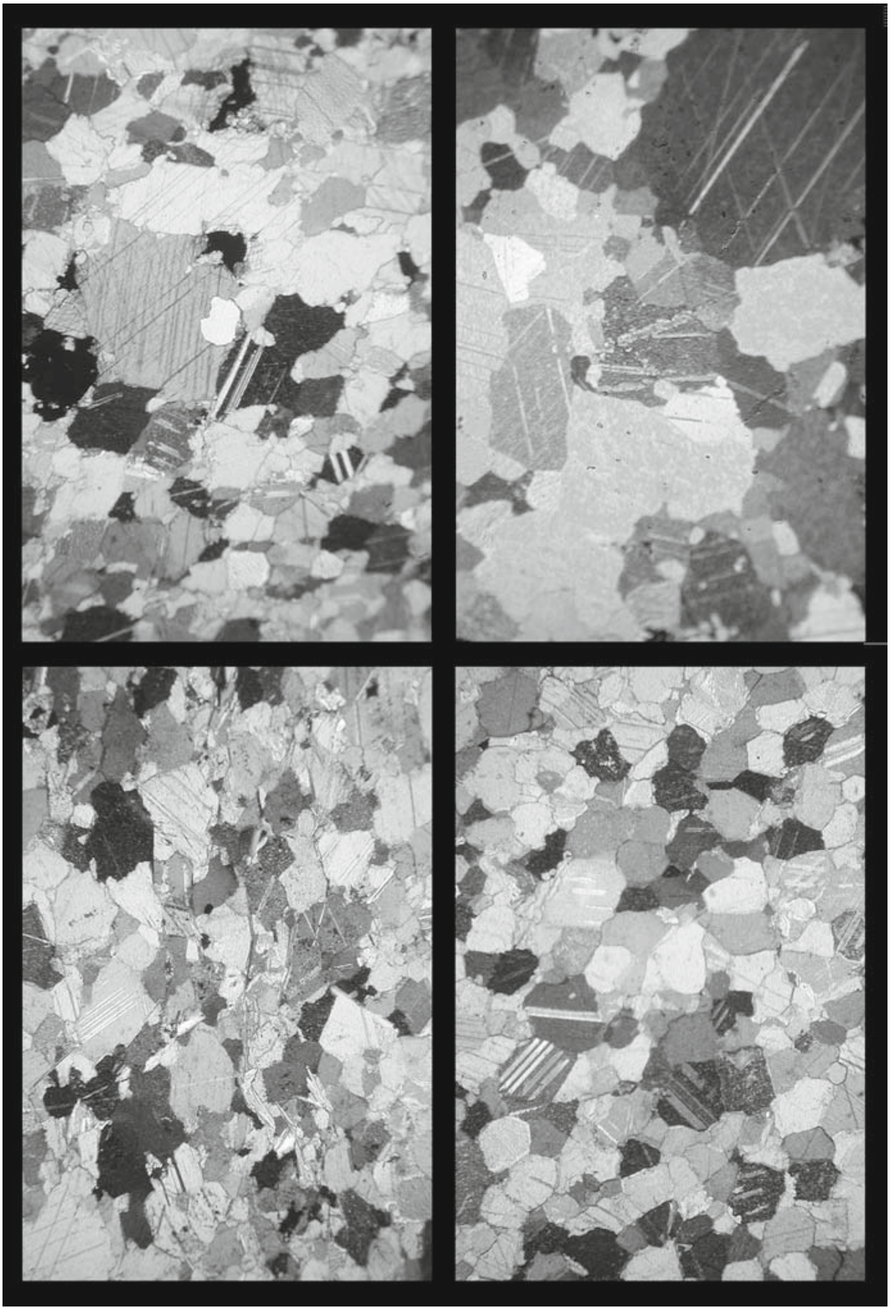

Fig. 5.8 Photomicrographs of thin sections of white marbles: *lychnites* from Stephani, Paros; Parian from Lakkoi; Peu Relic; Carrara (*left* to *right*, *top* to *bottom*)

Table 5.1 Results of the mineralogical-petrographic and isotopic analyses of the marbles of statuary and their relative provenance

Statuary and reliefs	Sample N°	Fabric		Calcite crystals boundaries	M.G.S. (mm)	Quartz	K-mica	Plagiocl.	Apatite	Carb. m./Graphite	Op. Min.	Dolo-mite (XRD)	δ ^{18}O PDB (−)	δ ^{13}C PDB (+)	Probable provenance
Head of Claudius Inv. 10460	CP1	HE	Mosaic	Embayed	1.70					+			3.32	4.22	Stephani, Paros (Greece)
Head of Caligula Inv. 5544	CP2	HO	Mosaic	Embayed	1.12	±				++	±		2.09	2.05	Carrara (Italy)
Statue of infant Inv. 55482	CP4	HE	Mosaic, slightly stressed	Embayed	2.88					+			3.69	1.85	Lakkoi, Paros (Greece)
Head of infant	CP5	HE	Mosaic	Curved/ embayed	2.40					++			3.01	5.07	Stephani, Paros (Greece)
Male seated figure Inv. 6955350	CP6	HE	Mosaic	Curved	1.60					++			3.39	4.89	Stephani, Paros (Greece)
Nike Inv. 2426 bis	CP7	HO	Mosaic, polygonal	Curved/ straight	0.64	±	±			++	+		1.87	2.34	Carrara (Italy)
Male torso Inv. 57055355	CP8	HE	Mosaic	Curved	2.25					+			3.47	5.21	Stephani, Paros (Greece)
Female statue Inv. 565/66	CP9	HE	Mosaic, slightly stressed	Curved/ embayed	3.10	±	±		±	+++			3.41	3.92	Stephani, Paros (Greece)
Relief with town Inv. S.69.4562	C2. 12	HO	Mosaic	Curved	1.04	+				+++		–			Carrara (Italy)

Table 5.1 (continued)

Statuary and reliefs	Sample N°	Fabric		Calcite crystals boundaries	M.G.S. (mm)	Quartz	K-mica	Plagiocl.	Apatite	Carb. m./Graphite	Op. Min.	Dolo-mite (XRD)	δ ^{18}O PDB (−)	δ ^{13}C PDB (+)	Probable provenance
Relief with town Inv. S69.4562	C2. 13	HO	Almost polygonal	Curved	0.72	±	±			+++	±	+	2.48	2.16	Carrara (Italy)
Fragment of wing of a statue	C2.9	HE	Mosaic, slightly lineated	Curved/ embayed	1.19	±	±	±	±	+++	+	−	2.16	2.13	Carrara (Italy)
Fragment of a foot	C2. 4	HE	Lineated, with fine-grained levels	Curved	0.90	+	+++	±	±	+++	+	−	1.49	1.87	Carrara (Italy)
Foot of a statue S78-7875	C2.5	HE	Mosaic, slightly lineated	Embayed	1.20	±	±			+++	±	−	4.04	2.51	Mount Penteli, Athens (Greece)
Fragment of the drapery of a statue	C2. 16	HE	Mosaic, slightly lineated	Embayed	1.10	+	±		±	+		−	3.46	2.39	Mount Penteli, Athens (Greece)

Explanation: M.G.S. = maximum grain size, HE = heteroblastic; HO = homeoblastic; +++ very abundant; ++ abundant; + present; ± traces

Table 5.2 Results of the mineralogical-petrographic and isotopic analyses of the marbles from architectural elements, and their relative provenance

Architectural elements and inscriptions	Sample N°	Fabric		Calcite crystals boundaries	M.G.S. mm	Quartz	K-mica	Plagiocl.	Apatite	Carb. m./Graphite	Op. Min.	Dolomite (XRD)	δ ^{18}O PDB (−)	δ ^{13}C PDB (+)	Probable provenance
Fragment of a lintel	CP 11	HE/HO	Mosaic	Curved/embayed	0.55					++			2.00	2.65	Carrara (Italy)
Lesbian Kyma Inv. 6.570	CP 10	HE	Mosaic	Curved	0.88				±	±	+		2.04	2.14	Carrara (Italy)
Inscription of the *Augustales*	C2. 1	HO	Polygonal with triple points	Curved/straight	0.64	±		±		+++		−	2.13	1.76	Carrara (Italy)
Inscription of *Brocchus* N° 1	C2. 2	HE	Mosaic, stressed	Sutured	3.84				±	++		−	1.18	2.07	Lakkoi, Paros (Greece)
Inscription of *Brocchus* N° 2	C2. 3	HE	Mosaic, slightly stressed	Curved	2.40		±			+		−	3.46	5.16	Stephani, Paros (Greece)
Corinthian capital of pilaster	C2. 6	HO	Mosaic, slightly stressed	Curved/embayed	0.66	±	±			++	+	−			Carrara (Italy)
Frame Inv. S70.21780	C2. 7	HO	Mosaic	Curved	0.88	±		±		++	+	−	1.98	2.32	Carrara (Italy)
Fragment of decorated pilaster Inv. S69.9292	C2. 8	HO	Almost polygonal	Curved	0.72	+	++			+++	++	−	1.84	2.05	Carrara (Italy)

Table 5.2 (continued)

Architectural elements and inscriptions	Sample N°	Fabric		Calcite crystals boundaries	M.G.S. mm	Quartz	K-mica	Plagiocl.	Apatite	Carb. m./Graphite	Op. Min.	Dolomite (XRD)	$\delta^{18}O$ PDB (−)	$\delta^{13}C$ PDB (+)	Probable provenance
Fragment of a decorated pilaster Inv. S69.57	C2. 10	HO	Almost polygonal	Curved/straight	1.02					+++	+	−	2.03	1.73	Carrara (Italy)
Fragment of Corinthian Capital Inv. S69.4210	C2. 11	HO	Polygonal with triple points	Curved/straight	0.58		±			+++	+	−	1.90	2.00	Carrara (Italy)
Fragment of Corinthian capital	C2. 14	HO	Mosaic	Curved	0.95	+		±		+++	++	−	1.89	2.15	Carrara (Italy)
Fragment of a slab Inv. TEA M 657	C2. 15	HO	Almost polygonal	Curved/straight	0.70					+++	±	−	2.23	1.92	Carrara (Italy)
Fragment of a Ionic column Inv. S70.15864	C2. 17	HO	Mosaic	Curved	0.65		±			+++		−	2.20	1.92	Carrara (Italy)
Fragment of frame Inv. S69.6009	C2. 18	HO	Almost polygonal	Curved	0.62					+++		−	1.93	2.10	Carrara (Italy)
Fragment of a Corinthian capital Inv. S69. 8896	C2. 19	HE	Mosaic, lineated	Curved	0.90	+	+++		++	+++	±	−			Mount Penteli, Athens (Greece)

Explanation: M.G.S. = maximum grain size, HE = heteroblastic; HO = homeoblastic; +++ very abundant; ++ abundant; + present; ± traces

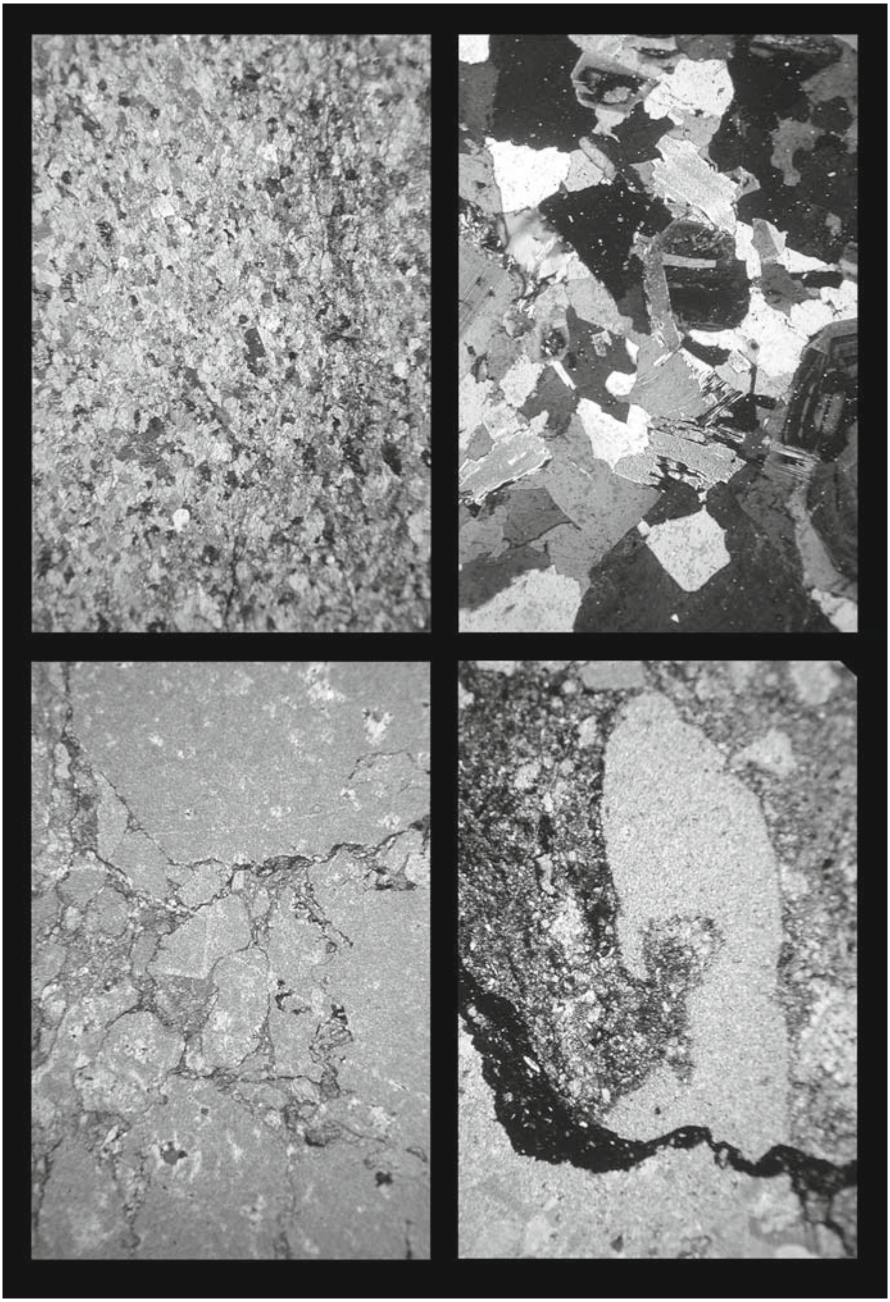

Fig. 5.9 Photomicrograph of thin sections coloured marbles: marmor taenarium, Elba granite, marmor sagarium, breccia of unknown provenance (see Fig. 5.13); breccia di settebasi (*left* to *right*, *top* to *bottom*)

Fig. 5.10 Coloured marbles from Asia Minor: pavonazzetto; africano; breccia corallina (*left* to *right*, *top* to *bottom*)

Peloponnesos), cipollino verde (from the southern part of the Euboea island) and porfido verde antico (from near Krokea, province of Sparta, Peloponnesos).

Italy: ardesia (from Liguria?), granitello antico (granite from the island of Elba).

North Africa (Fig. 5.12): Greco scritto (from Hasançausear near Ephesus-Turkey, or from Cap de Garde, near *Hyppo Regius*, modern Annaba, Algeria; this is a true marble usually included among coloured species), giallo antico (from ancient *Simitthus*, modern Chemtou, Tunisia).

To these materials has to be added a beautiful polychrome breccia (Fig. 5.13) so far of unknown provenance. It is polymictic, i.e., composed of angular clasts of different colours (whitish, grey, red) and degrees of roundness, all of calcareous nature. The white and grey clasts may be classified as biomicrites (Folk 1959), or wackestone (Dunham 1962) showing abundant plates and spines of echinids and non-skeletal algae. Red clasts are typical micrite/mudstone coloured by finely-dispersed hematite and containing calcareous radiolarians, fragments of pelagic

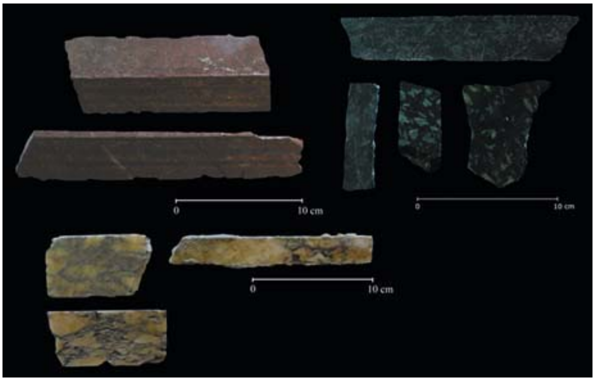

Fig. 5.11 Coloured marbles from Greece: marmor taenarum, lapis lacedaemonius, breccia di settebasi

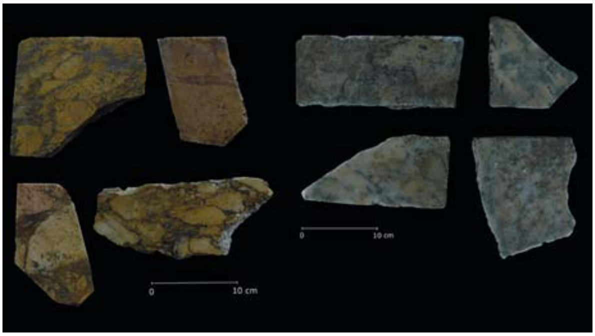

Fig. 5.12 Coloured marbles from North Africa: giallo antico; greco scritto (*left* to *right*)

bivalves (so-called philaments) and spines of sponges. The boundaries of all clasts are marked red by deposition of hematite, also present in stylolites and sometimes cumulating with angular quartz and phyllosilicates.

Table 5.3 gives an approximate evaluation of the abundance of the coloured marbles (indicated also with their ancient Roman names, when known) of the *opera sectilia* of the theatre.

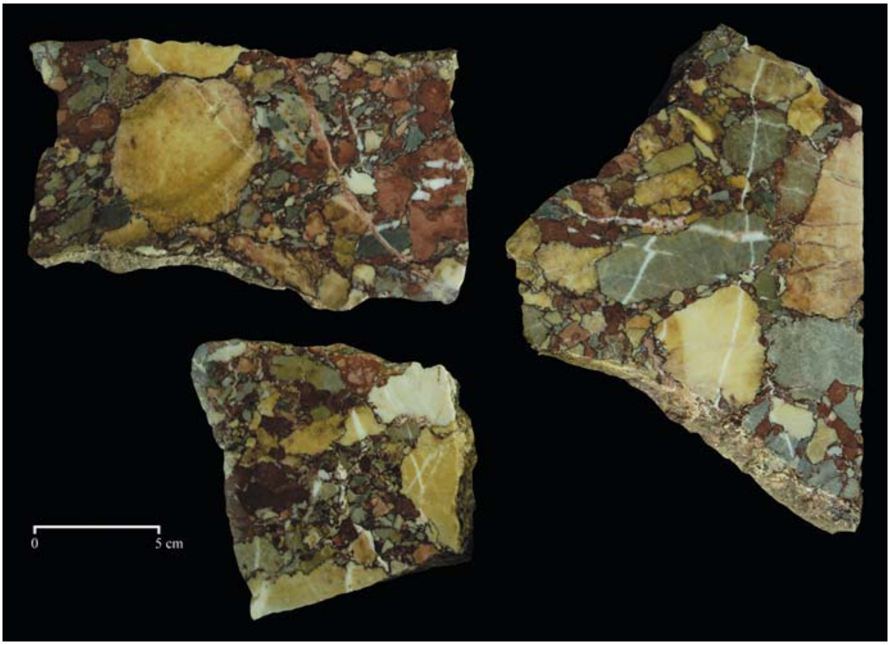

Fig. 5.13 Polychrome breccia of unknown provenance

Table 5.3 Relative abundance (+++, very abundant; ++, abundant; +, present; ±, traces) of slabs of coloured marbles in the *opera sectilia* of the theatre

Ancient Roman name of the lithotype	Modern name	Relative abundance
marmor lucullaeum	Africano	++
marmor sagarium	breccia corallina	±
marmor docimenum, m. phrygium	pavonazzetto	++
	breccia di settebasi	+++
marmor thessalicum, lapis atracius	verde antico	+
marmor chium	portasanta	+
marmor taenarium	rosso antico tenario	++
marmor lacedaemonium	serpentino, porfido verde antico	±
Lapis niger?	ardesia (slate)	+
	greco scritto	++
marmor numidicum	giallo antico	+++
	unknown polychrome breccia	++

5.4 Conclusions

The identification of the white and coloured marbles of the theatre of *Copia* has made it possible to reconstruct the decorative elements of some of its important parts.

Namely it seems that:

- the *scaenae frons* was decorated with columns of coloured marbles such as bigio antico and breccia di settebasi (also used for the small niches containing statues of white marbles), and of granite columns from the island of Elba;
- the statues were of white marble from the island of Paros, Luna and Mount Penteli; the architectural elements were of Luna marble;
- the floor of the orchestra and the walls were decorated with *opera sectilia* made with slabs of coloured marbles from Greece, Asia Minor, Italy and North Africa.

On the basis of these results, we may deduce an imperial *munificentia* (commissioning) for the theatre, or that very rich patrons offered some of the best decorative materials available on the market at the end of the 1st century and the first half of the 2nd century A.D.

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Chapter 6
Black “Marble”: The Characteristic Material in the Baroque Architecture of Cracow (Poland)

Mariola Marszałek and Andrzej Skowroński

6.1 Introduction

The oldest examples of architectural use of Polish black limestone date back to the late 16th century. The rock was commonly applied starting from the beginning of the 17th century, both as a structural and decorative stone used above all in tombstones and epitaph tablets, but also in fragments of altars, inner and outer portals, railings, floor slabs, baptisteries, even whole chapel interiors, etc. The rock became so popular because it is very suitable for being polished, resulting in glassy, mirror-like surfaces. The black, solemn colour was thus a perfect choice in the Counter Reformation period. The sculptors working in Dębnik, where the quarries were situated, and in Cracow, the then capital of Poland located nearby, produced countless works of small-scale architecture that spread all over the Commonwealth of Two Nations, as Poland was called. In terms of its territorial range, Poland was then the largest country in Europe, reaching the Dnieper and the Dvina to the east; and it consisted of two united parts, i.e., the Crown lands of proper Poland and the Grand Duchy of Lithuania. As a result, examples of the use of the Dębnik limestone are so numerous that in the Polish history of art the 17th and 18th centuries have been given the name “the period of the black marble”. It should be added that artifacts made of the Dębnik limestone were widely exported to the neighbouring countries. Today they can be found, e.g., in Germany (Frankfurt am Main) and Austria (Vienna, Graz, Salzburg) (Rajchel 2004; Niemcewicz 2005).

Black marble-like limestones and marbles were also commonly used in Baroque architecture all over Europe. Some occurrences of these rocks are well known on a regional scale, among others in Belgium (Namur province: *Belge Noir*—Upper Devonian, eastern Belgium near Sankt Vith: *Rechter Blaustein*—Lower Devonian),

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Germany (Aachen: *Aachener Blaustein*—Lower Carboniferous; Zehnder 2006, Schupbach near Limburg: *Schupbach Marmor*—Middle Devonian), northern Italy (the Southern Alps, the region between Lake Como and Lake Garda: *Calcare di Varena, Grigi Carnico, Nero di Rovere*—Triassic; Marinoni et al. 2002, 2007), Spain (Vizcaya province near Marquiña: *Negro Marquiña*—Cretaceous, Alicante province, the Betic External Zone: *Jabalina Stone*—Triassic; Benavente et al. 2006) and Switzerland (the Northern Alps: *Alpenkalk*—Triassic and Jurassic; Zehnder 2006). The stones mentioned here without reference have been found on respective web pages, where they are identified as black in colour, although in the web photographs the colour of not all of them seems to be really black. The Dębnik limestones being Middle Devonian are one of the oldest rocks among those specified above.

6.2 Materials and Methods

6.2.1 Characteristic of the Stone

The deposits of black, compact limestone discussed in this chapter occur in the southern part of Poland, about 20 km west of Cracow, in the vicinity of the Dębnik village. The rock is of the Middle Devonian age and represents Givetian (Fig. 6.1; Narkiewicz and Racki 1984; Baliński 1989; Bednarczyk and Hoffmann 1989). Another deposit of black limestone, but with stones of inferior quality, is situated in Kajetanów (the Holy Cross Mts, central Poland). They were used on a very limited, regional scale.

The Dębnik limestone also known as the Dębnik marble (although the name "marble" should properly be limited to metamorphic rocks) was recorded as early as the Middle Ages. The first reference about quarrying the Dębnik stones comes from 1415 (see Rajchel 2004). In the 17th and 18th centuries there were 15 or so quarries close to the Dębnik village. The oldest of them, with stones of the best quality and owned by the monks from a nearby monastery of the Discalced Carmelites, has been duly named the Carmelite quarry (Fig. 6.2). The rocks quarried include pelitic limestone with fossils as well as detrital and laminated limestone (Bromowicz 2001), making up approximately 36 and 41% of the profile, respectively. The third type, i.e., homogeneous, pelitic limestone, makes up the remaining 23%. The average thickness of the limestone beds usually ranges between 40 and 60 cm. Fossils identified in the limestone include corals, brachiopods, pelecypods, gastropods, and hydrozoans (*Amphipora* sp. and *Stromatopora* sp.).

The decorative properties of the Dębnik limestone include its deep black colour and taking excellent polish, as well as the presence of veins, fossils, and sparite calcite nests within the micritic background. These elements combined with structural and textural features provide a diversified appearance to polished stone surfaces. Considering the Dębnik limestone as an ornamental material, three varieties have been distinguished:

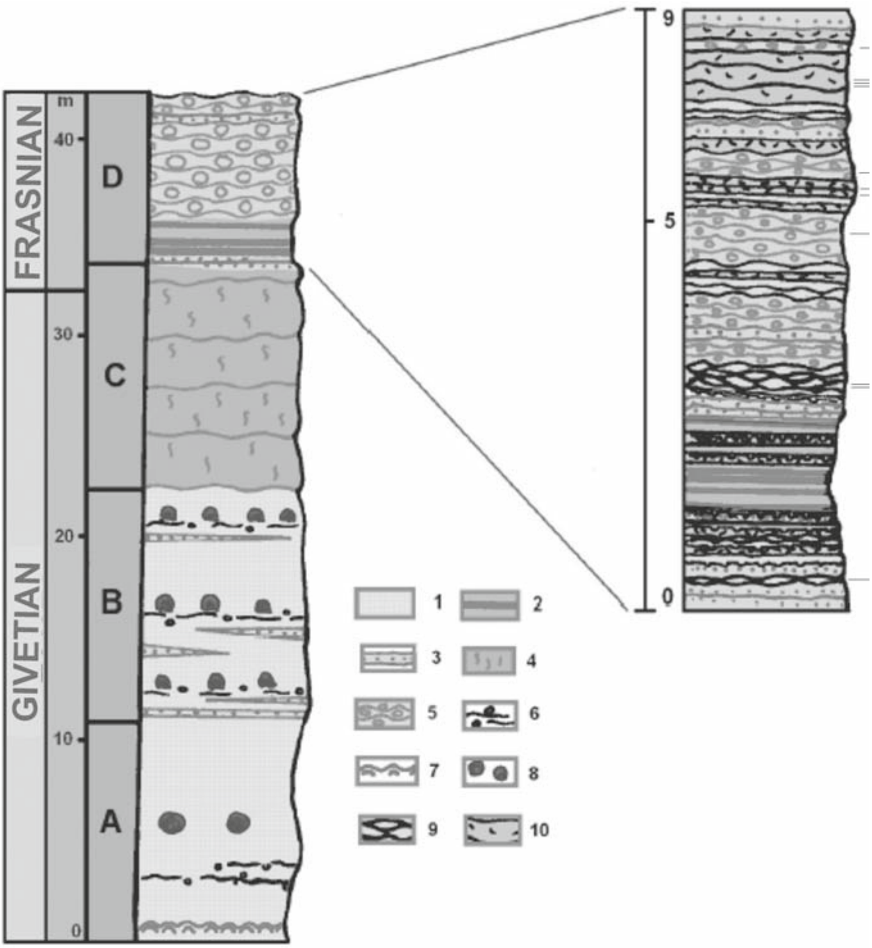

Fig. 6.1 Simplified profile of the Dębnik limestones (after Bednarczyk and Hofmann 1989). **1** pelitic limestones, **2** marls, **3** detrital limestones, **4** bioturbated pelitic limestones, **5** nodular limestones, **6** erosional surfaces, **7** stromatolites, **8** stromatoporoids, **9** streaky-nodular limestones, **10** concentrations of fossil shells (Reproduced by permission of Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH-UST)

- homogeneous, black pelitic limestone;
- homogeneous, black pelitic limestone with fossils;
- heterogeneous, black and dark grey detrital limestone, laminated in places and intercalating with the pelitic variety.

Work has now been initiated to restart quarrying in Dębnik. The uppermost parts of the profile, about 15–20 m thick, do not meet requirements, due to the undulated structure and thin bedding of the stone, and a lower level needs to be developed.

Selected physical and mechanical properties of the limestone have been given after Bromowicz (2001) for lower parts of the Dębnik and Dębnik I quarries. This is

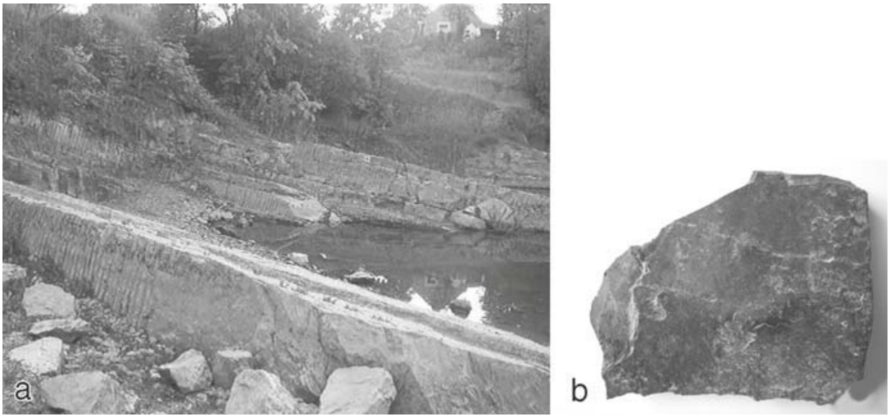

Fig. 6.2 **a** Old Carmelite quarry—marks after wedging of stone blocks can be seen (photo by courtesy of M. Wójtowicz), **b** black limestone displaying a deep black colour in its inner part

limestone corresponding to the Dębnik limestone that was extracted centuries ago in the historic quarries mentioned above. The properties determining the durability of the rock when exposed to the atmosphere are apparent density, water absorption, frost resistance, abrasion resistance, and strength resistance. They were measured according to Polish standards (see Bromowicz 2001 for details).

The apparent density of the Dębnik limestone (2.68 tm^{-3}) classifies the rock as very heavy. Its water absorption is very low (<0.5%) to low (0.5–5%), with an average value of 0.29%. Consequently, the low water uptake results in the high frost resistance of the rock.

The compressive strength in the air-dry state (58–194 MPa, average 119 MPa) characterizes the Dębnik limestone as of medium and high resistance. The abrasiveness of the Dębnik limestone using the Boehme method (0.16–1.18 cm, average 0.34 cm) classifies it as having medium and low abrasiveness. Two systems of joints promote the working out of blocks with sizes up to 2 m.

These technical properties of the Dębnik limestone are very advantageous and they ensure good preservation of the stone elements when worked out. The influence of atmospheric factors results however in uniform or spotty whitening of the stone and considerably lowers its aesthetic value. Even a short walk along Cracow streets reveals changes in its appearance. Exposition to atmospheric factors, especially of the stones situated outdoors, changes their original black colour, fading to grey or even white; and the stone, if polished, loses its shiny appearance. These effects can be widely seen in architectonic elements but can also be observed in outcrops. Superficial whitening, or as some call it, greying or bleaching, of the Dębnik limestone when exposed to a polluted, urban atmosphere is combined with deposition of anthropogenic particulates on the stone surfaces, which makes a plausible explanation of the phenomenon additionally difficult.

6.2.2 Sampling

The material analysed was collected from the Carmelite quarry in Dębnik and it represents homogeneous limestone, including both fresh and weathered varieties. The latter shows changes from its original black colour into grey or even white.

The natural, fresh samples were used for identification of stone components, especially of the non-carbonate fraction. These samples were mortar-crushed and dissolved in diluted HCl (1:10), providing the first part of the acid-insoluble grain fraction. The other part was obtained from the acid-insoluble fraction calcined at 700°C to remove organic matter. This procedure was applied to identify and quantify the non-carbonate components. These results were reported in part by Marszałek and Muszyński (2001) and Marszałek (2007). More detailed analyses of organic substances were made of the extracts, obtained from the solid residue treated with C_2Cl_4. The weathered parts of the Dębnik limestone were used for identification of changes in composition of the outer stone layers.

6.2.3 Analytical Techniques

6.2.3.1 Inorganic Fraction

The mineralogical, chemical, and microstructural characteristics of the stone were obtained by optical microscopy and scanning electron microscopy, X-ray powder diffraction (XRD) and X-ray fluorescence (XRF) analysis.

Optical and scanning electron observations were made of the universal polished thin sections cut perpendicular to the stone surface. Additionally, broken surfaces of inner (non-weathered) and outer (weathered) parts of the samples were observed using the SEM/EDS method. XRD analyses were performed on bulk samples, insoluble residues, and weathered layers of the stone. Chemical analyses were carried out using the XRF technique.

Typical mineralogical equipment included: an optical microscope Olympus BX 51, a field emission scanning electron microscope FEI Quanta 200 FEG with energy dispersive spectrometer EDAX, an X-ray diffractometer Philips X’Pert APD and an XRF analyser Philips PW 2400, all of them working in standard conditions, and are therefore not specified here.

Another method was applied in order to characterize the chromatic properties of the fresh limestone and its weathered layers. They were measured using a Konica Minolta CM-2500d colorimeter, equipped with Xenon lamps as a source of light in the spectral range of 360–740 nm, applying a viewing angle of 8°and an illumination area with a diameter of 8 mm.

6.2.3.2 Organic Fraction

The characteristics of the organic compounds were obtained using FTIR spectroscopy, Rock-Eval pyrolysis and gas chromatography combined with mass spectroscopy GC-MS.

The FTIR analyses were made for both the acid insoluble fraction of bulk samples and the solid fractions left after treating a sample with HCl and then separating out C_2Cl_4-soluble organic extracts and letting them evaporate. Rock-Eval pyrolysis was made on the bulk and weathered parts of the stone and provided information on the nature of the organic substances and respective differences between these two layers. These differences are expressed by hydrogen HI (mg HC/g TOC) and oxygen OI (mg CO_2/TOC) indices. Total organic carbon TOC was estimated by LECO analyses as well. The components of the organic matter (identified in the form of methyl esters because of an analytical procedure; Hermosin et al. 2004) were investigated using GC-MS analyses.

The research equipment included a FTIR Bio-RAD model 165 spectrometer, a GC8000/MD/800 gas chromatograph in combination with a mass spectrometer, a Rock-Eval II pyrolyser, and a LECO apparatus.

6.3 Results and Discussion

6.3.1 Mineralogical and Petrographical Study

The Dębnik limestone from the Carmelite quarry is biomicritic with generally nodular fabric and undulatory bedding, revealing few microveins and stylolites. In some sections of the profile the limestone is compact, with fewer fossils.

Carbonate components are represented by micritic calcite with traces of dolomite. Non-carbonate components include K-feldspar, smectite, illite, occasionally pyrite and organic substances, as well as traces of detrital quartz and hydromuscovite. The organic matter concentrates are parallel to the bedding (Fig. 6.3).

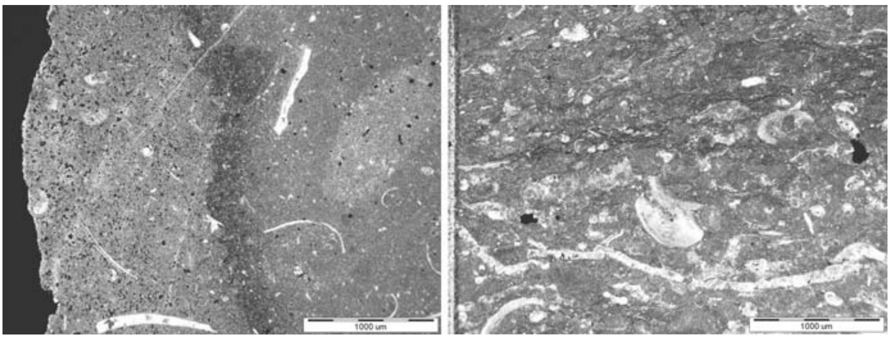

Fig. 6.3 A lamina of the organic matter. Optical microscope, one polaroid

The Dębnik limestone is composed (XRF analyses) mainly of CaO – 53.92 wt.%, accompanied by minor amounts of SiO_2—1.2 wt.%, Al_2O_3—0.53 wt.%, K_2O—0.45 wt.% and MgO—0.85 wt.%. Recalculation of the total CaO gives 96.3 wt.% of calcite; silica alumina, and potassium are contained mainly in feldspars and clays; whereas magnesium probably in dolomite. Other elements occur in traces and do not exceed 0.0X wt.%. The rock can therefore be considered a relatively pure limestone.

The total amount of pyrite in the Dębnik limestone is about 2 wt.% but this mineral is distributed rather erratically. Pyrite is represented by two populations of grains:

1. Crystals that are various combinations of cube, dodecahedron and octahedron, with sizes 0.002–0.025 mm. They are a dominant pyrite type; and
2. Euhedral, cuboidal crystals with sizes reaching 2 mm (Fig. 6.4).

The organic content in the whole of the rock samples was estimated at 0.30 wt.% TOC (TOC—total organic carbon) which represents 4.4 wt.% of the HCl–insoluble fraction (Marszałek and Muszyński 2001). The correlation between hydrogen (HI) and oxygen (OI) indices in Rock-Eval pyrolysis points to the type III of kerogen, i.e., the kerogen derived from humic organic matter of probably algal and bacterial origin (Marszałek 2007).

The FTIR results (Fig. 6.5) indicate that the organic matter is composed mainly of aliphatic long-chain hydrocarbons (characteristic bands around 2930 and 2960 cm^{-1}, due to oscillation within the CH_2 and CH_3 groups, respectively). The remaining part of the spectra in the range 2000–500 cm^{-1} is inherently complex and difficult to interpret. Only the band around 1740 cm^{-1} can be ascribed to the presence of carboxyl groups. There are no aromatic condensed hydrocarbons in the samples as can be inferred from the lack of bands around 3040 cm^{-1}. The organic compounds yield complex mass chromatograms (GC-MS), in which fatty acids, saturated (e.g., nonanoic, decanoic, undecanoic, dodecanoic, tridecanoic, tetradeca-

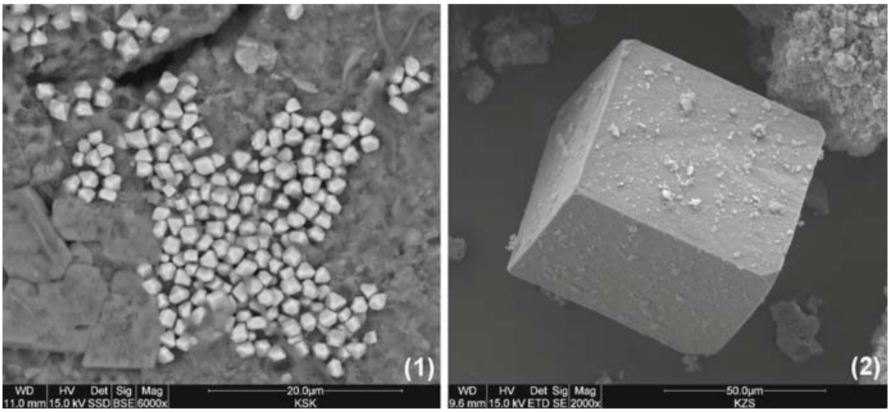

Fig. 6.4 SEM micrograph of euhedral pyrite crystals (type 1/type 2)

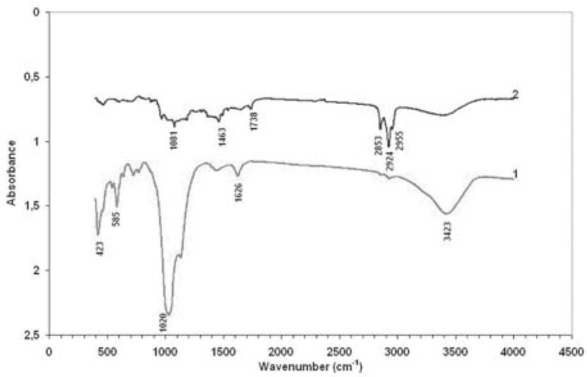

Fig. 6.5 FTIR spectra of the **1** acid insoluble fraction of the bulk sample and **2** evaporated C_2Cl_4 extract of the HCl-insoluble fraction

noic, pentadecanoic, hexadecanoic, octadecanoic, heneicosanoic), and unsaturated (hexadecenoic and octadecenoic), n-alkanes C_{16}–C_{20}, (hexadecane, heptadecane, octadecane, eicosane), aromatic hydrocarbons and policyclic hydrocarbons predominate (anthracene, pyrene).

The black colour of the Dębnik limestone is thought to be caused by an admixture of bitumens (Gradziński 1972; Kozłowski and Magiera 1989; Lewandowska 1998) or pyrite (Bednarczyk and Hoffmann 1989). The stone spontaneously releases a smell of petroleum if hit with a hammer.

The grey to black colour of the sedimentary rock can have been induced by organic substances as well as by iron pigment. Organic matter is a very common component of carbonate rocks averaging 0.33 wt.% TOC (Lewandowska 1998). The colour change of the rock expected during weathering may be attributed to stability of the pigmenting carbon compounds, of which in sedimentary rocks hydrocarbons, asphalt and kerogen are possible. The hydrocarbons, being the least stable carbon pigment, particularly the aromatic hydrocarbons, determine the dark colour of the sediments. Dark grey and black limestones bleach quite easily to light grey after a few years exposure to weathering (oxidation environment). Reactions with aggressive solutions present in the ambient air enhance colour changes towards a very light shade (Winkler 1997).

On the other hand, iron is the most common and strongest pigment in sedimentary rocks. It can give the stone the colours from deep red to orange, yellow, brown, or tan to green, blue and black, depending on the ferric/ferrous (Fe^{3+}/Fe^{2+}) ratio in the given rock. The deep grey to black colour of the stone is connected with the predominance of ferrous iron. In this case Fe^{2+} may occur as finely distributed pigment that is bluish green to black and results from the presence of pyrite and/or marcasite (FeS_2). The powder (i.e., streak) of these minerals is actually black, although when recrystallized to larger grains the minerals become yellowish-brass. These ferrous sulphides are formed in a reducing environment. The presence of organic matter in the limestone is proof of such a reducing environment in a sedimentary basin, in which sulphates are reduced to hydrogen sulphide with further formation of iron dioxides (Lewandowska 1998). Iron pigments in sedimentary rocks are generally unstable if exposed to weathering and light, but the degree of colour stability is hard to predict.

6.3.2 *Weathered Surfaces of the Limestone—The Quarry*

The change of the original colour of the outer stone parts in the case of the homogeneous Dębnik limestone is the main sign of stone weathering. In another variety—the nodular limestone that occurs in the form of horizontal layers separated by discontinuities filled with clay minerals—exfoliating is also visible.

The changes of colour measured between bulk limestone and weathered layers reveal that the total colour change ΔE* is mainly due to the lightness variation ΔL*. The differences of the chromatic coordinates, Δa* and Δb*, are much lower (Table 6.1). The results cannot be univocally interpreted, as the measurements had to be made using broken, uneven surfaces that bear signs of alterations. Anyway, a marked shift of the b* values towards positive values in the case of the weathered samples means that these rocks have become yellowed. It is a far going assumption whether such a change may be associated with the presence of pyrite.

No secondary mineral phases have been found (XRD); and observations using scanning electron microscopy revealed that the outer surface often shows karst-like alterations and signs of leaching, but is covered only by fine calcite grains (Fig. 6.6). Similar descriptions were given by Kozłowski and Magiera (1989) and Wilczyńska-Michalik (2004). Additional microstructural changes measured between the bulk and the weathered part of the stone were noticed. The outer, i.e., weathered part of the stone (ca. 20–30 μm), is characterized by discontinuities and intra- and inter-crystalline microfractures, which are parallel to the surface and grade into an unaltered, massive rock. The inner part of the black limestone, reveals a compact structure and low porosity (Fig. 6.7). Some authors explain this phenomenon as thermal cracking of the calcite crystals. The cracking is caused by the anisotropy of thermal expansion of calcite grains due to differences between the thermal expansion coefficients along the *a* and *c* lattice directions (Marinoni et al. 2007). Other authors suggest that the stress resulting from changes of air temperature (this process starts at about 40–60°C) can impart microfractures among mineral grains (Winkler 1997; Marinoni et al. 2007).

Similar effects were observed when studying the fractal recurrence of karst phenomena. One of them was represented by the constant presence of an optically whitened layer on the surface of rock undergoing weathering (karstification). In hand specimen inspection, particularly using a binocular, this layer strongly resembles

Table 6.1 The values of chromatic parameters (L*, a*, b*) and total colour differences (ΔL*, Δa*, Δb*, ΔE*) in the samples from the Carmelite quarry

Sample	L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*
KB1	34.64	0.01	−0.09	15.64	0.37	4.16	21.50
KW1	50.31	0.38	4.07				
KB2	36.14	−0.06	−0.3	23.51	0.61	4.95	24.03
KW2	59.65	0.55	4.65				
KB3	32.12	−0.05	0.29	25.7	0.07	6.04	26.40
KW3	57.82	−0.12	6.33				

KB – bulk black limestone, KW – weathered layer

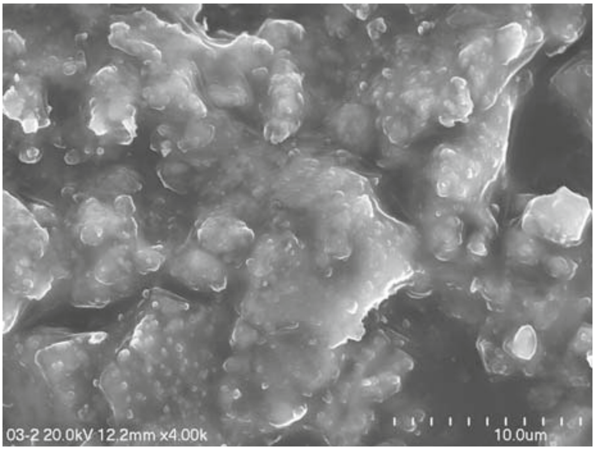

Fig. 6.6 SEM micrograph of outer, weathered part of the stone, revealing fine grains of calcium carbonate only and signs of leaching

fine-grained sugar. Under a scanning microscope the grains from the surface were distinctly loosened, standing out of the compact, massive rock typical of the sections unaffected by weathering. The transition from these almost loose grains into the massive, uniform rock was always smooth and gradual. The thickness of the loosened layer depends on the size of the grains and the cohesion of the rock. The layer could be even some millimetres thick if weathering was advanced (personal communications from J. Wrzak, M.Sc., a speleologist).

The study of the TOC, HI and OI (Rock Eval) parameters can be summarized as follows. These indices are higher in weathered layers than in unweathered (inner) parts of the stone (Table 6.2). Those differences could be connected with the presence of microorganisms on the surface of the stone. The presence of bioactivity was

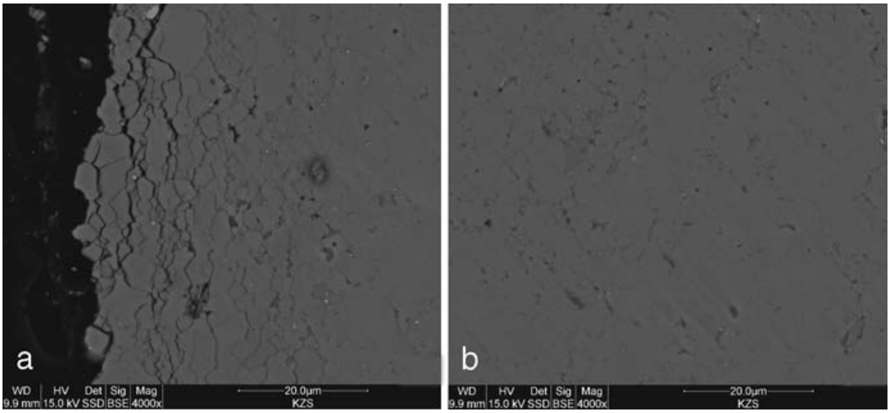

Fig. 6.7 SEM micrograph of a black limestone transversal section: **a** highly fractured weathered black limestone surface, **b** inner part of the black limestone, highlighting a compact structure of the stone and low porosity

Table 6.2 Rock-Eval data measured in the unweathered and weathered samples of black Dębnik limestone

Sample	TOC	T_{max}	S_1	S_2	S_3	PI	HI	OI
KB/04a	0.19	–	0.06	0.03	0.51	0.75	15	268
KB/04b	0.18	–	0.08	0.05	0.54	0.67	27	300
KW/04a	0.23	431	0.18	0.62	0.77	0.22	269	334
KW/04b	0.22	431	0.16	0.61	0.72	0.21	277	327

TOC – total organic carbon, T_{max} – temperature, S_1 – mass of the hydrocarbons, released at 300°C (mg HC/g), S_2 – mass of the hydrocarbons, released at 300–600°C (mg HC/g), S_3 – mass of CO_2 (mg CO_2/g), PI – index = $S_1/(S_1+S_2)$, HI – hydrogen index (mg HC/g TOC), OI – oxygen index (mg CO_2/g TOC)
KB – bulk sample of Dębnik limestone; KW – weathering layer

confirmed by scanning electron microscopy, which showed traces of lichen activity and microorganisms on the Dębnik limestone surface (Fig. 6.8).

6.3.3 Weathered Surfaces of Monuments—Cracow City

Historical elements exposed to a polluted atmosphere reveal the presence of the bleached surface as well (Fig. 6.9), but the composition of the surface is different from that of the rock surface in the natural outcrops. Some elements are covered by gypsum layers and contain other anthropogenic particles, mainly aluminosilicate glass spherules, iron oxides, partly coked carbon particles. In some architectonic details alveoles or surface exfoliation are developed. Their presence depends on the texture of the Dębnik limestone variety used, its orientation towards the bedding, and localization in respect to atmospheric factors.

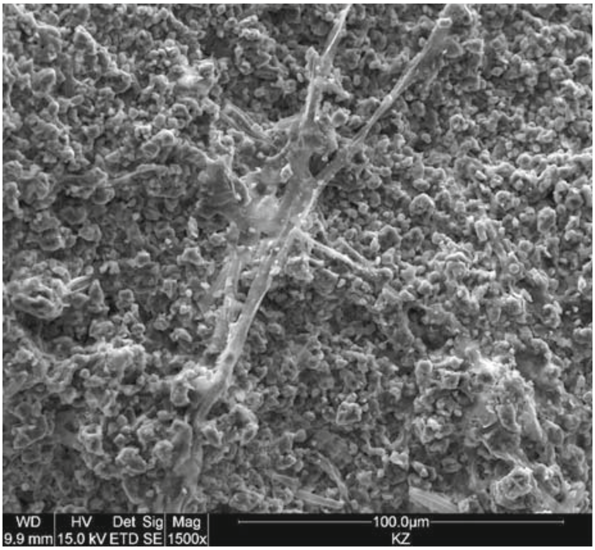

Fig. 6.8 Bio-activity on the black limestone surface—SEM micrograph

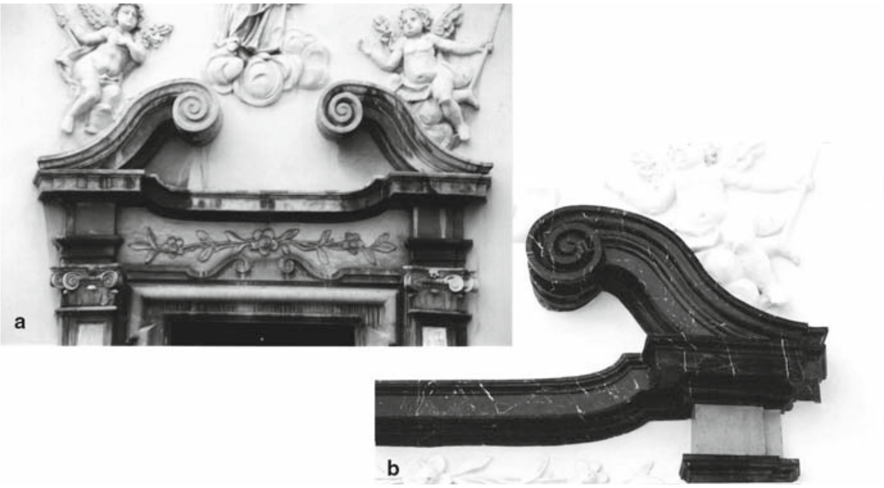

Fig. 6.9 Upper part of the portal constructed from Dębnik limestone—at St. Adalbert Church in Cracow **a** before and **b** after cleaning

The way the stone blocks are cut controls their further destruction:

- along discontinuities—results in exfoliating and cracking;
- perpendicular to discontinuities—gives rise to the formation of alveoles.

The processes of weathering of the black Dębnik limestone visible in architectonic details were discussed in Kozłowski and Magiera (1989) and in more detail by Marszałek (2004, 2007), and Marszałek et al. (2006).

The phenomena of the bleaching of black compact limestones were studied over the last few years by Marinoni et al. (2002, 2007); Benavente et al. (2006); and Zehnder (2006). All these authors emphasize colour changes of a variety of black compact limestone from black to grey or even white during exposure to climatic influences and they explain the changes as being optical effects taking place on the weathered, porous surfaces of the stone. On the polished surface of the dense and dark stone, the light is mostly absorbed, opposite to the weathered one, where light is reflected from the porous surface and scattered by the grain boundaries. As a result, the surface takes the colour of the disintegrated powder material, known to mineralogists as streak; and the streak of calcite, disregarding its colour, is white. When treating such an uneven surface with a liquid such as oil (e.g., linseed oil with an index of refraction 1.48), the pores become filled with a medium of optical properties similar to the minerals of the stone (calcite with indices of refraction $n_\varepsilon = 1.486$ and $n_\omega = 1.658$) and the original black colour of the stone comes back. It is a novel approach to the problem of colour changes, bearing in mind that most common explanations involve such phenomena as the weathering of organic matter and pyrite or the formation of secondary mineral phases on the stone surfaces.

Generally, the methods applied by the authors mentioned above in studying the processes of greying of black limestone are rather similar. On the whole, the results obtained do not provide clear-cut evidence to explain the chromatic weathering (i.e., greying, whitening) of the black “marbles”.

6.4 Conclusions

The variety of Dębnik limestone used widely in the Baroque period in small-scale architecture in Poland is a black, homogeneous, micritic rock with fossils and white calcite veins and nests. Besides calcite, the limestone contains subordinate amounts of feldspars, clays, pyrite and organic matter of the kerogen type, and traces of quartz and hydromuscovite.

Both the artifacts made of the Dębnik limestone and the rocks exposed in the quarry show patches or zones whose original colour fades to grey or even white. In the quarry the depth of these changes reaches a fraction of a millimetre. Of the components present within the rock, its black colour is imparted by pyrite and organic matter. Weathering of these two is commonly blamed for the decolouration of the black limestone, but no new mineral phases have been observed in Dębnik. This rather excludes pyrite and suggests that the changes may be associated with alterations of organic compounds. On the other hand, the changes of rock cohesion in the topmost layer with a thickness of 20–30 μm may cause some optical phenomena resulting in colour changes. They may include scattering of the light on the rough rock surface, i.e., on the grain boundaries, with simultaneous lowering of light absorption. Nevertheless, the problem remains open.

The reasons for the colour changes observed in the architectonic elements made of the same stone in Cracow are more complex. Newly formed gypsum is commonly present in surface layers of the Dębnik limestone; and the surfaces themselves are usually covered by particulate matter. Both these components are of anthropogenic origin and effectively hinder full explanation of the phenomenon. The presence of the gypsum layer on the surface of limestone is so common in the polluted urban atmosphere that most authors dealing with the problem of colour changes limit themselves to precipitates and particulates of anthropogenic origin.

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Chapter 7
Understanding the Long-Term Survival of Sandstone in Medieval Ecclesiastical Structures: Northern Ireland and Western Scotland

Stephen McCabe and Bernie J. Smith

7.1 Introduction

7.1.1 Understanding the Performance of Stone in Monuments

Much of the world's, and especially Europe's, built heritage has been constructed using natural stone. Historically, it is a building material that is both aesthetically pleasing and durable. However, contrary to common perception, stone is not immutable, and many of our valued stone-built historic structures show obvious signs of age and decay. Advanced decay leads to the irrevocable loss of irreplaceable cultural heritage. Because of this, much effort has gone into understanding natural stone decay and the ways in which it may be managed. This focus on decay has meant that the reasons why certain stones survive are rarely examined. The long-term survival of stone over many centuries is a very complex problem—for example, factors that might be expected to cause decay can sometimes increase durability, depending on a specific combination of history, environment and stone character. To begin to understand this, a clear picture of history (events that have had impact on stone in the past), environment (the related processes that the stone is exposed to) and stone character (both material and form) is crucial. This chapter begins by emphasising the importance of each of these factors in understanding the long-term pattern of decay and survival of medieval sandstones. Following this, case studies are presented on the use and performance of sandstones in two medieval ecclesiastical structures in Northern Ireland and western Scotland—Bonamargy Friary and Iona Abbey, respectively. These structures are examined because they are exemplars of medieval structures that have been subjected to long and

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complex histories, from environmental extremes to conservation intervention and restoration. Northern Ireland and western Scotland experience a similar temperate maritime climate. The study of these sites is useful because historic sandstone structures are often found in coastal areas because of trade routes: for example, Iona Abbey may seem isolated from a present day perspective, but in medieval times it was a hub of activity due to the trade route it was located on—according to MacArthur (1995, p. 10), the abbey was situated in “a practical and strategic spot”. Furthermore, sandstone structures in coastal locations warrant study because they often suffer from accelerated decay due to the potentially aggressive (relative to non-maritime temperate environments) weathering environments in which they are situated. The abundance of moisture and marine salts means that salt weathering (and associated mechanisms of decay) is a particularly troublesome problem at coastal sites. Historic sandstone decay in coastal areas, therefore, deserves considerable attention.

7.1.2 Importance of Stress History

Inheritance is a widely documented concept in geomorphology (Thornes and Brunsden 1977; Warke 2007; Thomas 2001; Brunsden 2001), and has been applied to building stones in recent times (Cooke et al. 1995; Warke 1996). Everything that a stone block experiences from its emplacement to the present-day will influence how it behaves in response to the environment it is subjected to (McCabe et al. in press). Thus, an understanding of past events that may, for example, have propagated stresses can help to account for the present-day performance of the sandstone, in that current decay forms are often a manifestation of inherited stresses.

To illustrate the complexity of this inheritance, information (including historical events that are likely to have influenced stone performance) regarding medieval ecclesiastical structures from Northern Ireland and western Scotland are summarized in Table 7.1. This table shows that, over the lifetime of a structure, stone can be subjected to many stresses, all of which have the potential to contribute to the present-day performance of the stone—lime rendering, removal of lime render, fire (sometimes multiple), Little Ice Age conditions, abandonment, conservation intervention and restoration. On top of these past events, there is also the present and future challenge of climate change.

The term ‘complex stress history’ describes the cumulative impact of past stresses on stone. It reflects an understanding that the response of stone to any applied stress is invariably cumulative, so that the immediate response of stone to a stress event will depend on previous stresses experienced, and will in turn help to determine response to any subsequent stresses. In this light, it is important to gather historical information on a structure to understand its decay. A helpful concept is that of ‘building pathology’, a developing idea, which has received increasing attention from researchers in recent years. ‘Pathology’ may be defined as the systematic study of diseases with the aim of understanding their causes,

Table 7.1 A summary of information on the subject monuments.

Name	Location	Date	Sandstones[a]	Significant events
Bonamargy Friary	Ballycastle, Co. Antrim, NI	1500	Fair Head Sandstone (varieties A, B and C)	Lime render and removal, fire, Little Ice Age (LIA), abandonment 1639, conservation intervention
Armagh Friary	Armagh, NI	1263	Brockram Sandstone	Lime render and removal, fire (twice), LIA, abandonment 1595, conservation and restoration
Dungiven Priory	Dungiven, NI	1100s	Dungiven sandstone (buff and pink)	Lime render and removal, LIA, abandonment early 1700s, conservation and restoration
Iona Abbey	Iona, Inner Hebrides, Scotland	1200, significant rebuilding in mid-1400s	Carsaig Sandstone	Lime render and removal, LIA, extensive restoration/stone replacement, abandonment (1560) and re-use (1630s). Complex modern restoration history
Killean Old Church	Killean, Kintyre, Scotland	1100s	Macrihanish Sandstone	Lime render and removal, LIA, abandonment 1770
Kilbrannan Chapel	Skipness, Kintyre, Scotland	Late 1200s	Arran Sandstone	Lime render and removal, LIA, abandonment 1692. Ongoing conservation by Historic Scotland.

[a] For specific sandstone characteristics, see Table 7.2

symptoms and treatment (Watt 1999). In the field of medicine, when pathology is investigated, knowledge of the patient's age, health and lifestyle is essential. A similar strategy should be employed in the investigation of historic sandstone structures, exploring their age, state of conservation, and complex stress history. Implicit within the concept of building pathology is the need for an individual, research-based, approach to the decay management and conservation of each historic sandstone structure. Each case should be treated separately, because no two structures, facades, or even single blocks, will receive exactly the same number, sequence, frequency, duration and magnitude of stress events (McCabe et al. 2007a; Brunsden 2001).

7.1.3 Importance of Environment

When attempting to understand long-term stone decay, it can be a mistake to emphasise the physical characteristics of stone over the environmental processes it is exposed to. Both are crucial to the stone decay system. Environmental scientists have played a vital part in bringing balance to this view, by explaining the importance of environmental controls on decay and durability, and the subtle ways in which they operate. From an environmental point of view, temperature and moisture cycles, over long periods of time, are the key underlying controls on the decay of historic sandstone.

Temperature is a crucial control on stone decay, acting through many processes (e.g., salt weathering) to bring about deterioration. However, temperature fluctuations themselves can directly induce thermal stresses in materials (Yatsu 1988). If a body is heated, it has a tendency to change its dimensions, and this is often in the form of expansion. For example, quartz grains making up a piece of sandstone may expand upon heating. If this natural expansion is prevented for some reason—for example, the presence of other quartz grains surrounding an expanding grain—thermal stress arises. It has been observed that temperature will not produce any stress in stone "providing that the body is homogenous, isotropic and unrestrained (free to expand)" (Kingery 1955, p. 3). However, Hall (1999) points out that in reality these conditions are very rare, and especially uncommon when stone is placed in the built environment (surrounded and restricted by mortar and other building blocks). Kingery states that when the perfect conditions above are not realised then "stresses will arise due to difference in expansion between crystals" (1955, p. 3). Differential expansion of the components that make up a rock, and of the crystalline minerals expanding in different orientations at different rates is a commonly cited cause of thermal fatigue (Yatsu 1988). Temperature fluctuations will encourage fatigue failure and the operation of other mechanisms of decay near the stone surface.

Moisture content and migration is perhaps the most crucial control on the nature and severity of decay processes (Turkington et al. 2002). It is in the presence of salts that moisture is most often considered, but moisture in a salt-free system can also cause damage (Snethlage and Wendler 1997). Dilatation and contraction can take place in sandstones due to moisture changes. For most sandstones, hydric dilatation is in the range of 500 $\mu m\,m^{-1}$, but clay-rich sandstones can reach 5000 $\mu m\,m^{-1}$ (Snethlage and Wendler 1997).

Understanding the day-to-day environmental factors that contribute to the complex stress histories of historic sandstone is essential to understanding how sandstone decays in the long term. It is in the context of background environmental factors (such as temperature and moisture cycling, salt weathering, biological deterioration, chemical alteration), occurring on a daily basis, that more extreme stress events (see Table 7.1) must be set. Background environmental decay processes are often exploitative in nature, and weaknesses (e.g., chemical alteration, microfracturing, pore alteration) created and developed by extreme events can facilitate the slow decay of historic sandstone by background environmental factors.

7.1.4 Importance of Stone Character

How a sedimentary stone was deposited will largely determine the character of the stone (see Weber and Lepper 2002)—its physical properties, durability and response to subsequent environments. A brief discussion of how stone character affects stone performance follows.

The physical properties of stone (e.g., the linked properties of porosity, permeability, density and compressive strength) of course have marked influence on the long-term durability and performance of a stone. Because moisture is one of the key underlying environmental controls of stone decay (see Sect. 7.1.2), porosity and permeability are very important—these determine how much moisture can enter the stone and hence play a large part in influencing the decay processes taking place. "The arrangement, size and shape of the pore system have a significant effect on the performance of materials in relation to water, frost, salt and chemical weathering" (Pavia 1999, pp. 34,35). Density is inversely related to porosity—how tightly grains are packed and how well they are cemented within a sandstone will influence the stone's resistance to exploitative environmental processes. Each of the above will contribute to the stone strength—"the response of rocks to stresses induced by frost and salt weathering mechanisms may ultimately depend upon their general cohesiveness which can be characterized as compressive strength" (McGreevy 1982, p. 277).

The mineralogy of a stone will also determine how it behaves in response to its environment. Quartz is the most common mineral in sandstones. It is resistant to both physical and chemical decay processes as it does not display any cleavage planes and dissolves only in the most extreme conditions. If quartz dominates the composition of a sandstone, this will be a very important control for the durability of the stone. Secondary minerals, however, are often not so resistant to decay, and these can play an important role in controlling the performance of the stone—feldspars, micas and clay minerals are all susceptible to exploitative processes, primarily because they are affected by moisture ingress into fractures and between structural sheets. "Decay may be accelerated by the presence of clay minerals. It has been shown that under laboratory conditions clay-rich laminae in sandstone break down more readily during salt weathering than those containing low clay concentrations" (Warke and Smith 2000, p. 1341).

Perhaps the most important control on the behaviours of the sandstones in this study is the cement that binds the quartz grains together. The presence of iron in sandstone cement and interstitial clays is receiving increasing attention from stone decay scientists. The selective mobilization and subsequent surface precipitation of iron in historic sandstones is common (seen in both Bonamargy Friary and Iona Abbey, Sect. 7.2), although they depend on the iron content of the stone. The problem of iron migration raises issues both of aesthetics and durability. The appearance of a block can alter significantly when iron is mobilized from the substrate and precipitated on the surface. From a performance perspective, when iron in the cement of a sandstone migrates from the substrate to the surface, the integrity of the stone interior can become seriously compromised. In extreme cases, iron crusts can form on the surface of the stone, which can initially stabilize the surface by increasing surface strength. However, once this hard crust is breached, rapid retreat may ensue (McAlister et al. 2003).

Stone thermal properties are also an important ingredient in influencing performance. The main factors that determine how a rock responds to temperature change are colour and thermal conductivity. “On light-coloured stone, crusts and stains effectively reduce albedo which may increase solar energy absorbance and hence surface temperature” (Warke et al. 1996, p. 295). If a sandstone surface has become soiled (or indeed stained by iron) then it is likely to experience higher temperatures than would a clean surface, increasing the efficacy of decay processes driven by temperature. Thermal conductivity properties will control the temperatures that a stone experiences at depth: a high thermal conductivity means that temperatures are conducted well through the material, resulting in a low surface temperature (also affected by moisture content as this increases the connectivity between grains and water has a higher thermal capacity than stone). High surface temperatures, then, are seen in stones with low thermal conductivity (McGreevy 1982). Surface/subsurface temperature gradients are very important because this is the zone in which many weathering mechanisms are concentrated (Warke et al. 1996).

Another aspect of stone character is ‘form’ (or shape), which merits a brief mention. The complex three-dimensional geometry of buildings provides opportunities for ‘convergent’ weathering as moisture, temperature and other environmental gradients intersect across corners. It is for this reason that architectural detail and carvings are particularly prone to decay. ‘Form’ may also refer to the surface morphology/micro-topography of stone, which has been shown to impact on decay. Surface roughening allows the accumulation of moisture, salts and general particulate material which can facilitate surface weathering processes. Roughening of the surface increases the specific surface area exposed and susceptibiliy to weathering. Roughening may develop into alveoli, where self-reinforcing decay can be triggered—it has been suggested that stone decay occurring in caverns may be encouraged by the particular microclimatic conditions influenced by the morphology of the cavern (Turkington et al. 2002).

Northern Ireland and western Scotland (from which case studies are taken, below) have an almost unparalleled variety of geology in such a small geographical space (Mitchell 2004). The sandstones deployed in the subject structures (summarised in Table 7.2) range from Carboniferous to Jurassic in age. They are mainly composed of quartz, but traces of clay minerals such as kaolinite and montmorillonite were detected by infrared spectroscopy (FTIR) and X-ray diffraction (XRD) (McCabe 2007). Furthermore, many of the sandstones used in subject monuments have iron cementing, which leads to surface staining, as well as having implications for durability and performance.

Table 7.2 Sandstones deployed in the subject monuments and their characteristics (author's own analysis)

Name	Age	Colour	Mineralogy	Grain Size	Water absorption (wt.%)
Fair Head A (Bonamargy Friary)	Carboniferous	Light Brownish Grey (Munsell 2.5Y 6/2)	Quartz, kaolinite, iron cement	0.5–2 mm. Coarse grained, poorly sorted	9.3
Fair Head B (Bonmargy Friary)	Carboniferous	Yellow (Munsell 2.5Y 7/6)	Quartz, kaolinite, iron cement	0.2–0.5 mm. Fine grained, moderately sorted	8.0
Fair Head C (Bonamargy Friary)	Carboniferous	Brown/Dark Brown (Munsell 7.5Y 4/4)	Quartz	0. 2 mm. Fine grained, very well sorted	4.8
Dungiven Sandstone (Buff) (Dungiven Priory)	Carboniferous	Light brownish gray Munsell 10YR (6/2)	Quartz, kaolinite	0.2–0.5 mm. Fine grained, well sorted	4.4
Dungiven Sandstone (Pale red) (Dungiven Priory)	Carboniferous	Pale red (Munsell 10R 6/3)	Quartz	0.2–0.5 mm. Fine grained, very well sorted	Not sampled
Brockram Sandstone (Armagh Friary)	Permian	Red Munsell (10R 4/6)	Quartz	0.2–0.5 mm. Fine grained, moderately sorted	Not sampled
Carsaig Sandstone (Iona Abbey and Cloister)	Jurassic	Light yellowish brown (Munsell 10YR 6/4)	Quartz, monmorillonite, glauconite, iron cement	0.2–0.5 mm. Fine grained, well sorted	3.9
Arran Sandstone (Skipness Chapel)	Permian	Red (Munsell 2.5YR 5/6)	Quartz, kaolinite, montmorillonite	0.2–1 mm. Fine to coarse grained, moderately sorted	3.8
Macrihanish stone (Killean Old Church)	Carboniferous	Yellow (Munsell 2.5Y 7/6)	Quartz, iron cement	0.2–0.5 mm. Fine grained, well sorted	Not sampled

7.2 In-Depth Case Studies

Bonamargy Friary (Northern Ireland) and Iona Abbey (western Scotland) exemplify medieval structures with long and complex stress histories. This section looks at these sites in more detail, providing information on present-day environment, history (illustrating how stress events have the potential to compromise stone strength over time), stone character and evident decay forms—the product of a long and varied exposure history, where high magnitude stresses have punctuated the slow build-up of stresses by day-to-day environmental factors. Common decay relationships are then discussed.

7.2.1 Bonamargy Friary, Northern Ireland

7.2.1.1 Location and Description

Bonamargy Friary is located at the mouth of the river Margy, approximately 1 km east of the town of Ballycastle, on the north Antrim coast of Northern Ireland (Fig. 7.1). The friary comprises three main rectangular buildings (all ruined)—the main church, the dormitory and the chapel (Bell and McNeill 2002), as well as a small gatehouse in the grounds of Bonamargy. The church extends away from the east window, with the chapel and the dormitory flanking it to the south and north, respectively. In considering stone decay, the dormitory building is the most complex part of the structure as it is constructed from three variations of Fair Head sandstone (discussed below).

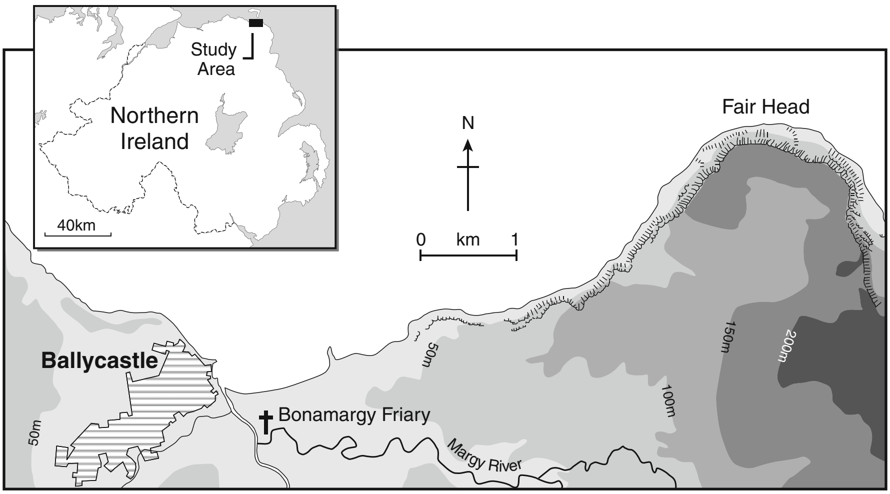

Fig. 7.1 Location of Bonamargy Friary on the north Antrim coast, Northern Ireland

7.2.1.2 Local Climate

British Atmospheric Data Centre (BADC) data for temperature and rainfall was analysed at sites within 2 miles of Bonamargy Friary (taken from the 1961–1990 base period). The average temperature graph shows a late summer maximum and a winter minimum, with a slightly wider range of temperature experienced in the summer months. The rainfall regime shows a late autumn/winter maximum (November), with a spring minimum (April/May). Average rainfall total during winter (N/D/J) is 296 mm, while the average summer rainfall (J/J/A) total is 224 mm. The summer/winter rainfall ratio (1:1.3) illustrates some seasonality at the site.

7.2.1.3 History and Potential Impact on Stone

Monument histories tend to be more dramatic in Northern Ireland, which had a war-torn character in medieval times (Nicholls 1972); Lynn (1975, p. 63) speaks of the "usual unhappy catalogue of decline and violence" seen in Northern Irish historic structures that have existed through the middle ages.

It is recorded that Bonamargy Friary was founded in 1500 by Rory MacQuillan (Bigger 1898), and was originally used by the third order Franciscan monks. In January of 1584 a battle was fought at the site of the friary, between the English MacQuillans, who had control of the friary, and the Scottish MacDonnells. A small garrison of the English was stationed at the Friary, and this garrison was attacked by the MacDonnells (Bell and McNeill 2002). During this attack, the MacDonnells "sett the roofe of the churche, being thatched, on fyer" (Bigger 1898, p. 15). Bonamargy was subsequently abandoned and left unoccupied between 1584 and 1621. The long-term impact of historical fire is not clearly understood, but recent work has been undertaken by McCabe et al. (2007b), who have demonstrated that stone response to salt weathering after exposure to fire is complex: the fire experiment reported by McCabe et al. (2007b) makes it clear that the blackening of stone from soot is an important by-product of fire, and the most obvious immediate surface effect. This soot cover brings with it the possibility of reduced permeability and hydrophobic tendencies, influencing subsequent exploitative decay processes. The surface soot-cover promotes surface/subsurface heterogeneity and can result in detachment of the artificial surface crust in the form of flaking, when salt concentrates and crystallizes beneath the surface. After the soot layer has become detached in this way (or perhaps been removed by cleaning), the exposed surface can exhibit rapid granular disaggregation caused by the alteration of the sandstone matrix through the extreme heat of the fire. The newly exposed surface can be expected to have a higher permeability caused by a combination of the fire event itself and the mechanisms of salt weathering.

In the case of many historic structures, the climate in which they are located has changed significantly during their lifetime (Smith 1996; Viles 2002; McCabe et al. in press). Bonamargy is no different, and the Little Ice Age (Grove 1988) (c. 1590–1850) is likely to have had a significant impact on the sandstones from which it was constructed. Recent research on reconstructing past environments in County Antrim, Northern Ireland, indicates that conditions were markedly wetter and colder during the LIA period (Swindles 2006). This suggests that freeze-thaw events may have been both more extreme and more frequent at this time in the structure's history. Such a regime of harsher past conditions can leave the stone with a stress legacy that can be exploited by environmental processes such as salt weathering (McCabe et al. 2007a).

In 1621, Randall MacDonnell, the then Earl of Antrim, made the friary habitable once more, and added a chapel and vault to the original buildings. It is likely that the present eastern window was also built at this time, having been destroyed during the 1584 sacking of Bonamargy. In 1637, the friary was given to the first order Franciscans, as a base for their mission to western Scotland. The last religious ceremony is recorded to have taken place in 1639, and since then the structure has been abandoned.

In the last century, extensive conservation intervention has been carried out at the friary, some of which has had a very significant impact on the decay pathways of the sandstones used in construction. The Northern Ireland Environment and Heritage Service (EHS) are responsible for the care of the monument. EHS records of conservation at Bonamargy Friary seem to begin in the late 1920s, but are often vague in their description of the works carried out.

A visit to the site reveals evidence of previous interventions that have had a negative impact on the performance of the Fair Head sandstone from which the friary was constructed. The friary itself tells a story of mis-conservation. For 'box-work' can be seen on the chapel, where rigid modern mortar (applied in the 1970s) has been used to re-point the soft sandstone walling of the chapel at Bonamargy Friary. The surface of the sandstone has retreated dramatically in a few decades, leaving the mortar to protrude from the façade. This inappropriate intervention has caused accelerated decay and major aesthetic deterioration of the chapel (Fig. 7.2).

Furthermore, iron bars and rods are visible in several places on the stonework, blocking windows and doorways. These may be seen as a deterrent to intruders or vandals, but cause their own damage to the friary. For many decades the impact of iron rods on stonework has been cited, with their corrosive expansion causing physical and chemical breakdown: "it is so well known that iron cramps and dowels damage stonework that their use can be regarded as an error in craftsmanship" (Schaffer 1932, p. 20).

7.2.1.4 The Sandstones Used

The characteristics of the sandstones used at Bonamargy are summarised in Table 7.2. The sandstone was quarried from Fair Head, a Carboniferous succession several kilometres from the monument. There are three main variations of the sandstone used at the Friary (designated Fair Head A, B and C). Fair Head A is light brownish grey in colour (Munsell 2.5Y 6/2). It is composed of coarse quartz

Fig. 7.2 'Rigid' mortar at Bonamargy Friary, causing 'box-work' appearance

grains and is very poorly sorted, with large pore spaces visible to the unaided eye. Fair Head A is often severely weathered and grains disaggregate very easily. Fractured quartz grains can be seen in thin section under the microscope (Fig. 7.3). Iron cementing is also visible under the microscope and severe iron staining is seen on the surface of many blocks of Fair Head A on the building. Fair Head B is yellow in colour (Munsell 2.5Y 7/6). The stone is regularly used as a dressing stone around windows and doorways, not just at Bonamargy, but also at various medieval sites

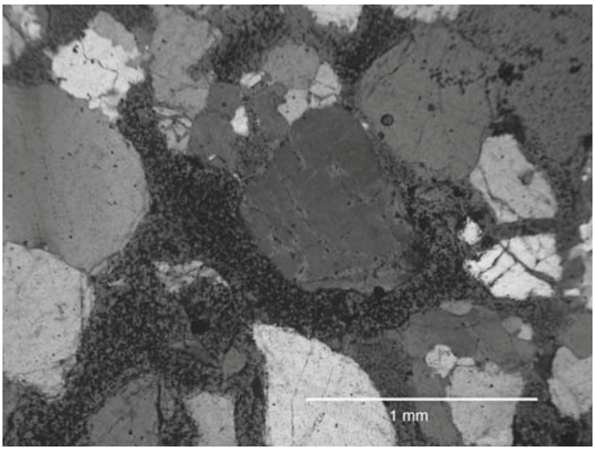

Fig. 7.3 Thin section photograph of Fair Head A

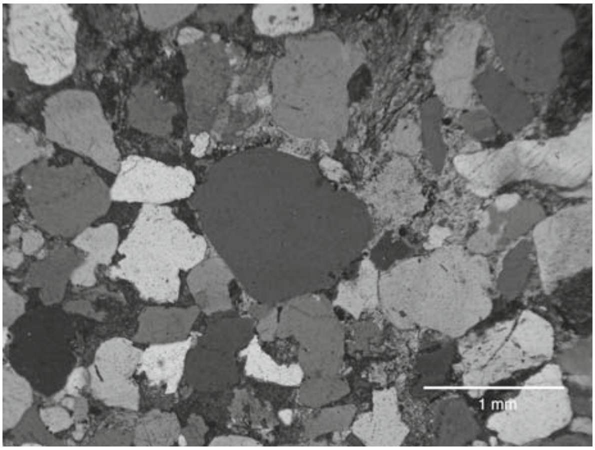

Fig. 7.4 Thin section photograph of Fair Head B

along the north Antrim coast (in a 15 mile stretch between Ballycastle and Portrush). It is composed mainly of sub-rounded, moderately sorted, quartz grains in iron-rich cement (Fig. 7.4). Iron spots are often visible on the surface of the stone, but staining is less severe than that of Fair Head A. Fair Head C is brown/dark brown in colour (Munsell 7.5YR 4/4). This stone is much finer grained than the previous two (quartz grains of less than 0.25 mm), and very well sorted with very tightly packed grains (Fig. 7.5). XRD traces show that the three variations of Fair Head Sandstone used in construction at Bonamargy Friary are mineralogically very similar, composed mainly of quartz, while decay illustrates the very different nature of their present day performance. From observations of performance in use, the most durable variation of Fair Head Sandstone appears to be Fair Head C, and the least durable Fair Head A.

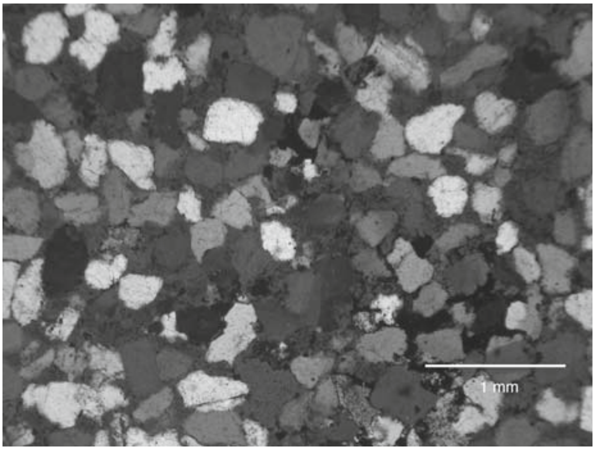

Fig. 7.5 Thin section photograph of Fair Head C

7.2.1.5 Decay of an East-Facing Façade-Section

Principal decay forms at Bonamargy Friary are summarized in Fig. 7.6. Figure 7.7 shows a map of stone types and decay from an east-facing façade section at the site. Fair Head A makes up 38% of the façade, with Fair Head B and Fair Head C making up 29% and 32%, respectively. Lichen growth is present on 25% of façade blocks, with alveolar weathering occurring on 12%, iron staining on 6%, and detachment of material on 5% of blocks. Fair Head A and B show a similar pattern of decay forms. Fair Head C blocks show extensive lichen growth, and only a limited amount of iron staining.

Each decay form shows clustering to a greater or lesser extent on this façade section. Iron staining, lichen growth and alveolar weathering all display pronounced clustering, while detachment occurs in small, disconnected, groups around the façade. The strong clustering on the east façade implies a dominance of environmental controls, although the clustering of iron staining reflects the clustering of stone types Fair Head A and B (sandstones which contain significant amounts of mobile iron, and exhibit greater susceptibility to exploitative decay processes).

7.2.2 Iona Abbey and Cloister, Western Scotland

7.2.2.1 Location and Description

Iona Abbey is one of the most historically significant monuments in the UK. Iona itself is inextricably linked to Columba, and in Early Christian times became a celebrated centre of religion. The Benedictine Abbey, founded in 1200, is the largest and most complex ecclesiastical monument in the West Highlands: "the disparity of scale and ornamental elaboration between Iona Abbey and all other churches in the Western Isles is so great that few direct examples of its architectural influence are identifiable" (The Royal Commission on the Ancient and Historical Monuments of Scotland 1982). The Abbey is located on the eastern shore of Iona, a mere 250 m from the Sound of Iona, close to Port Ronain (see Fig. 7.8), and overlooked from the west by Cnoc Mor. The medieval abbey is made up of the main church (nave, transept, chancel and sacristy) and the cloister walk adjacent to the north wall of the church.

7.2.2.2 Local Climate

Due to the lack of appropriate data specific to Iona Abbey, BADC data was taken from Dunstaffnage, approximately two miles from Oban, which provides a good example of an exposed location on the west coast of Scotland. The climate of western Scotland echoes that of the north Antrim coast. Though following similar annual

Principal decay forms	Observations / contributing factors	Photograph
Alveolar Weathering	Exposed coastal site, and salt carried inland from the sea is the likely cause of the alveoli. Gypsum was identified within the hollows at Fair Head, and it was suggested that salt weathering was the dominant process responsible for their formation (McGreevy 1985). Associated with iron staining.	
Lichen growth	Lichen is the most widespread decay feature. It is possible to see lichen that has become integrated into the stone surface detaching from the stone and thus bringing surface grains of sand with it (pictured). Lichen often works in combination with salts.	
Iron Staining	Surface iron staining is a widespread feature at Bonamargy (in extreme cases, case hardening, pictured), largely due to the use of Fair Head A, highlighting the strong lithological controls on decay seen at the Friary.	
Detachment	Especially interesting are scars of flaking, visible on each of the facades (pictured). Where flaking is recent, fresh stone is visible (and often has loose grains at the surface).	

Fig. 7.6 Summary of principal decay forms at Bonamargy Friary

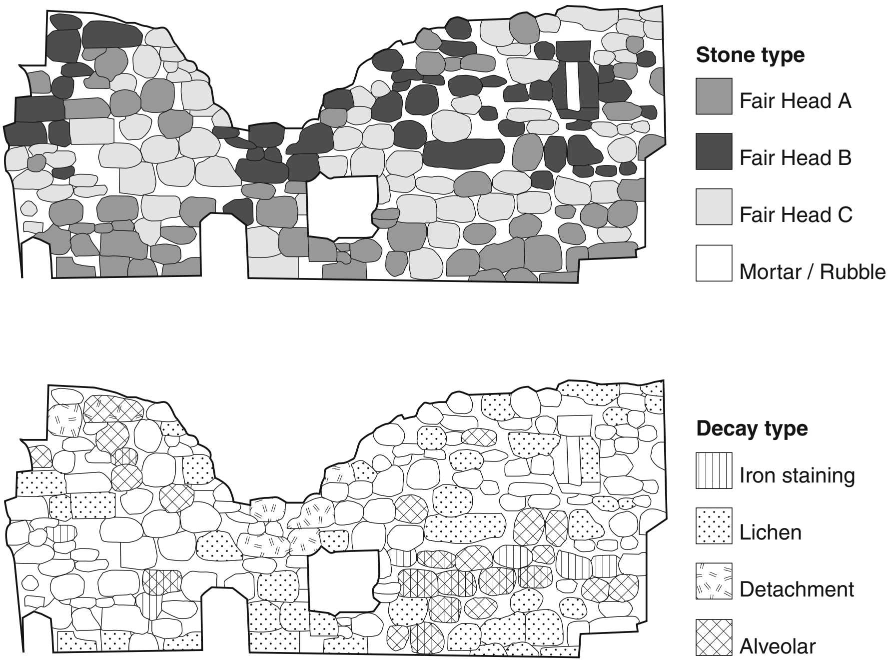

Fig. 7.7 Decay map of an east-facing façade section at Bonamargy Friary, showing stone types and decay forms

temperature and rainfall patterns, temperatures are slightly higher (average summer temperatures reach 17°C), and the Scottish coastline is significantly wetter than the Northern Irish. Average total winter rainfall (D/J/F) is 552 mm, while average summer rainfall (J/J/A) is 308 mm. The Scottish Atlantic coast is potentially very seasonal, with a summer/winter rainfall ratio of 1:1.8. This is a very exposed, potentially aggressive, weathering environment.

7.2.2.3 History and Potential Impact on Stone

While western Scotland does not have the same record of conquest and violence related to its historic monuments (compared to Northern Ireland), other important issues are raised when looking at the Scottish structures; for example, Iona Abbey has a very complex restoration history, which must impact on the decay pathway of the building. Similarly to Bonamargy, Iona Abbey would have been subjected to wetter, colder conditions during the LIA.

The original Romanesque stone church, cruciform in shape, was constructed in approximately 1200. However, little of the original building remains. The cloister was constructed in the 13th century. There is no evidence for further building

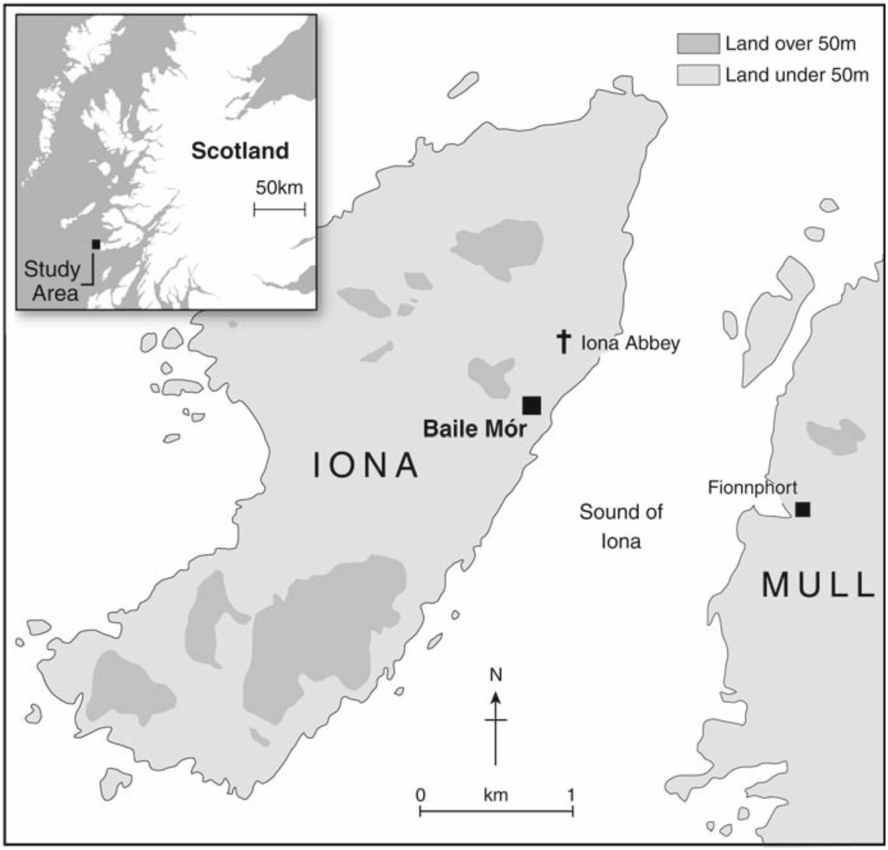

Fig. 7.8 Location of Iona Abbey on east coast of Iona, western Scotland

until the middle of the 15th century, when the south side of the church and east wall of the presbytery were demolished and rebuilt (resulting in a wider choir and nave). The majority of the present day structure dates to this 15th century rebuilding. The nave is much restored, but the choir, transepts and south aisle contain many exquisite original carvings (Ritchie and Harman 1996). The abbey buildings were abandoned and became derelict following the Scottish Reformation of 1560. In the 1630s it came into use once again, with the eastern parts of the church being restored, although work done during the 1630s has been removed in the course of later restorations (Royal Commission on the Ancient and Historical Monuments of Scotland, RCAHMS 1982).

A programme of restoration was undertaken between 1874 and 1876 by architect Rowand Anderson. He showed restraint in a time when many restorations were poorly executed in the UK (MacArthur 1995). The church was restored during this programme of work. In September of 1899, the ownership and care of Iona Abbey passed from the Duke of Argyll to a committee of Iona Cathedral Trustees, made up of principals from Scotland's ancient universities, and from the Church (MacArthur

1995). It was the desire of this committee that further restoration work be undertaken at the Abbey. The choir, transepts and crossing were restored in 1902–1905 by architects Ross, MacGribbon and Honeyman and the nave was restored in 1908–1910, by P. MacGregor Chalmers.

With restoration in the early 1900s came "controversy over what was or was not authentic" (MacArthur 1995, p. 85). An archaeologist, J. Romilly Allan, voiced his concern, hoping that there would "be no 'tinkering' with Iona Cathedral as its chief attraction for artists lay in 'its ruinous and desolate appearance'" (MacArthur 1995, p. 85). In an anonymous letter to the *London Chronicle* at the time, one person stated that "anything done to these ruins beyond what may be necessary to preserve them from falling to pieces would be a grievous blunder" (MacArthur 1995, p. 85). However, the Iona Cathedral Trustees stood firm and the restoration went ahead. The complex restoration history of Iona Abbey brings to life the perennial debate of those who think "restoration… is a lie from beginning to end" (Ruskin 1849, p. 200) and those who believe historic structures can and should be returned to their original appearance (e.g., Voilet le Duc). This debate is beyond the scope of this paper, but is an interesting aside in understanding the use and replacement of natural stone in built-heritage.

The restoration of the cloister, clearly visible in a visit to the abbey, was directed by Ian G. Lindsay in 1959. Where the restoration of other parts of the abbey appears to have been very successful, the restoration of the cloister seems to have been misguided. Figure 7.9 shows grooves in the restored stone (a rapidly retreating surface exhibiting severe granular disaggregation) making up the columns of the cloister walk. Where there are examples of the original Carsaig Sandstone (seen in four of the existing columns), it is apparent that this stone surface is stable, with no active material detachment taking place. "When it is desired to replace old decayed stone with new, it is necessary to give careful consideration to the choice of new stone" (Schaffer 1932, p. 95). This mis-restoration of the cloister walk at Iona Abbey highlights the importance of a research-based approach to restoration: each monument/building should be dealt with as an individual, with restoration tailored to the specific environmental conditions to which the stone will be subjected.

A further inappropriate intervention evidenced at Iona Abbey (but commonly seen around conservation and construction sites) is the use of unwashed sand in repointing mortar. Figure 7.10 illustrates salt being washed out of the mortar between granite blocks and down across the dressing sandstone. In an already salt rich environment, this could load stressed sandstones with salt, potentially causing further severe material loss.

7.2.2.4 The Sandstones Used

The main building stone of the Abbey is a pinkish granite, quarried from adjacent Mull. The fine grained dressing sandstone is Carsaig Sandstone (Munsell 5Y 7/4, pale yellow, with flecks of green from the presence of glauconite), also from the Isle of Mull (see Table 7.2 for general description). The sandstone is of Jurassic age, and appears to be a suitable and successful dressing stone. Carsaig Bay, where the sandstone was quarried, is situated on the south-east corner of Mull, where geological

Fig. 7.9 Rapid decay of restored stone (1959) in the cloister, Iona Abbey

successions of up to 60 m vary from pale green (glauconitic) stone to buff in colour. Glauconite is high in potassium and iron-rich. Under intense weathering conditions glauconite has the tendency to destabilise to a kaolinite and iron oxide assemblage (Brindley and Brown 1980). Perhaps because of this, the RCAHMS (1982) suggests that the stone “possesses poor weathering-qualities” (1982, p. 249). However, although decay of the stone at Iona Abbey is very severe in some places, the stone has proved its durability. Carsaig Sandstone was deployed in construction at the friary as early as the 12th century, and some of the more recent replacement stones (used, e.g., in the 1959 restoration of the cloister walk) have not performed so well, exhibiting severe detachment and preferential retreat in the form of granular disaggregation (see above, Fig. 7.7). The quarry at Carsaig was still being worked shortly before the middle of the 19th century, and was briefly reopened in 1875 to supply stone for the post-medieval restoration of Iona Abbey by R Rowand Anderson.

7.2.2.5 Decay of the East Window

Principal decay forms at Iona Abbey are summarized in Fig. 7.11, and a map of these decay forms on the east window is seen in Fig. 7.12. The proportion of Carsaig

Fig. 7.10 Salt from unwashed sand in repointing mortar migrating across block surface at Iona Abbey

Sandstone blocks exhibiting decay is similar to Fair Head A and B at Bonamargy Friary (alveolar weathering 5%, detachment 17%, Lichen 28% and iron staining 4%). This suggests that Carsaig Sandstone is similarly susceptible to decay processes. However, it should be remembered that Iona Abbey is approximately 300 years older than Bonamargy Friary and, in the context of length of service life, the original Carsaig Sandstone is in relatively good condition. Lichen growth is again the dominant decay feature, but levels of material detachment, alveolar weathering and iron staining are significant. The east window at Iona Abbey exhibits the most decay of any external sandstone feature at the site, which is in agreement with the work of Robinson and Williams (1996) on the role of aspect in stone decay (although the advanced decay may be less to do with cardinal compassed points than the specific macro-environment—the window faces onto the Sound of Iona). Much of the fracturing on the vertical jambs may be related to structural loading, but these can certainly be exploited by salt weathering mechanisms in this exposed coastal environment.

Lichen growth and material detachment show clustering, implying a dominance of environmental controls. Iron staining and alveolar weathering occur more in isolated blocks (although alveolar weathering occurs in some small disconnected groups). This suggests that lithology is the major control on the processes resulting in iron staining (confirming results from Bonamargy Friary) and alveolar weathering. At Bonamargy Friary, alveolar weathering tended to cluster, and a similar

Principal decay forms	Observations / contributing factors	Photograph
Alveolar Weathering	Iona Abbey is very exposed to the Sound of Iona and the Atlantic Ocean, with wind-blown marine salts likely to be deposited regularly on the stonework.	
Lichen growth	Lichen growth is widespread at Iona Abbey, especially on the east-facing window, where marine moisture is often deposited.	
Iron Staining	Iron staining is widespread. Carsaig Sandstone contains glauconite, which, when weathered, breaks down to form kaolinite and iron oxides. This may contribute to iron migration and precipitation in the stone.	
Detachment	Evident at the scale of flaking, or greater. Granular disaggregation is widespread. In extreme cases, fracturing of rock is visible, but this is likely to be related to structural loading, and exploited by salt weathering.	

Fig. 7.11 Summary of principal decay forms at Iona Abbey

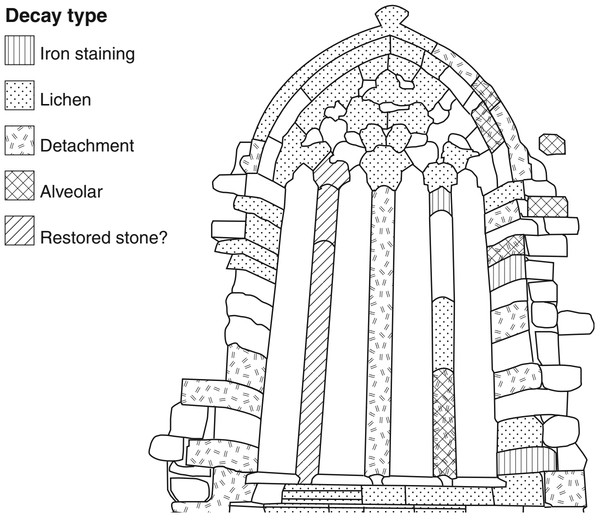

Fig. 7.12 Decay map of Iona Abbey East Window, showing decay forms

response might have been expected here with the proximity of the Sound of Iona. However, this is not the case and it may be that Carsaig Sandstone is relatively resistant to salt attack, with some blocks being further along the temporal decay pathway than others, owing to their unique complex stress history combined with specific block characteristics.

7.2.3 Influences on the Decay or Survival of Sandstones in Bonamargy Friary and Iona Abbey

In the field, environmental processes and mechanisms rarely act in isolation. Whether stone decays or survives is commonly the result of complex interactions between different decay processes that act in synergy, and lithology (the resisting force of the material). As a result, linking process to decay form (especially over the long time periods experienced by the sandstones in this study) can be problematic. However, the mapping and discussion of façades allows a clearer picture of decay forms to be appreciated. The processes which are likely to be acting (often in synergy) to bring about decay can then be deduced by highlighting patterns in decay form relationships. A brief discussion of common decay relationships seen at Bonamargy and Iona Abbey follows.

7.2.3.1 Iron-Staining and Alveoli—Decay or Survival?

Alveolar weathering is commonly associated with the action of salts. It is likely that the alveoli seen at Bonamargy Friary and Iona Abbey were formed by the deposition, ingress and precipitation of marine salts (and also encouraged by iron migration and precipitation: discussed below). Salt weathering is not invariably the cause of tafoni formation, and there is still uncertainty about the processes involved in the development of cavernous weathering (Turkington and Paradise 2005). However, salts are often present in alveoli back-walls and can cause material loss through the synergy of physical and chemical processes. For example, disaggregation of grains (alveolar weathering is also associated with detachment in the form of granular dissaggregation) and pore-infilling by salts may coincide with mineral dissolution. Because of the relatively alkali nature of salt solutions, they are capable of dissolving, transporting and precipitating some minerals (Goudie and Viles 1997). Iron dissolution and re-precipitation is an example of this, and the correlation of alveolar weathering and iron staining on blocks especially at Bonamargy Friary (Fig. 7.7) would suggest that physical and chemical salt weathering mechanisms are acting in synergy to form alveoli. The formation and development of alveoli is often associated with the case-hardening of proud/upstanding areas of the stone surface, which is commonly a result of the mobilisation and precipitation of iron cement: "honeycombs are the result of the removal of sand grains by salt weathering (crystallization) simultaneously with the case-hardening of walls and tendrils" (McBride and Picard 2004, p. 734). In the conceptual model of alveoli development proffered by Turkington and Paradise (2005), case-hardening (from the surface re-precipitation of minerals like iron) is a precursor to alveolar weathering, with the surface hardening being breached by subsequent weathering and the weakened subsurface rapidly retreating. Thus, at Bonamargy Friary, alveolar weathering and iron staining may be seen as the synergistic relationship of the physical and chemical action of salts, in combination with specific stone properties.

Different behaviour is seen at Iona Abbey (Fig. 7.12). On this decay map, alveolar weathering and iron staining do not occur on the same blocks. Here, iron-staining appears to have enhanced the durability of the stone, without the formation of alveoli causing a breach in the hard iron-crusted surface. Stones at Bonamargy Friary and Iona Abbey may be seen as at different stages along a decay path. Perhaps because of greater amount of precipitated iron on Carsaig Sandstone, the surface has not yet been breached; where iron-staining is seen, the surface is stable. Fair Head A and B at Bonamargy, further along the decay sequence, have commonly experienced breaching of iron-crusted surfaces that have developed into alveoli. The present-day stability of iron-crusted surfaces on Carsaig Sandstone does not preclude future breaching and rapid decay.

7.2.3.2 Lichen Growth—Decay or Survival?

The feature that most often shows clustering over the mapped façades and features is lichen growth. Lichens are the result of a symbiotic relationship between fungus (the mycobiont) and algae (the photobiont). The clustering of lichens is to be expected because lichens, as living organisms, can spread across mortar joints onto adjoining blocks by simple growth (Turkington and Smith 2004; McCabe 2007). This widespread appearance of lichens implies a dominance of environmental controls on lichen growth (i.e., conditions that support the organism). There is some debate, raised in the literature, over whether lichens increase deterioration or protect the stone surface from decay. The results of mapping the façades studied in this chapter suggest that the behaviour of lichens (that is, whether they contribute to decay or not) is controlled by lithology. Lichen growth can be associated with stable surfaces, where aggressive decay is not evident (e.g., Fair Head C Sandstone at Bonamargy Friary and Carsaig Sandstone at Iona Abbey). Conversely, granular disaggregation related to the action of soluble salts and lichen is commonly seen on Fair Head A. In the first instance, the sandstones are made up of tightly packed and well-sorted grains (Fair Head C is fined grained with a water absorption capacity of 4.8% by weight; Carsaig Sandstone is fined grained with a water absorption capacity of 3.9% by weight), leaving little pore space for the infiltration of lichen hyphae. The sandstones that are negatively affected by the physical action of lichens are those that are more porous, with a weak bonding of matrix and quartz grains, allowing lichen hyphae to surround the surface and nearsurface grains (Fair Head A is coarse grained and poorly sorted, with a water absorption capacity of 9.3% by weight). Grains are then incorporated into the lichen thallus and plucked from the stone surface as the lichen expands and shrinks in response to moisture (Duane 2006). This integration of mineral fragments into the lichen thallus is an important aspect of the biophysical decay caused by the organism (Bjelland and Thorseth 2002). The action of salts with lichen hyphae is common in causing material detachment at subject sites. Salts may originate from the chemical reaction of the lichen-secreted acids with the mineral substrate (Chen et al. 2000). Once salts form, they may work in synergy with the lichen hyphae in the physical disruption of the near-surface zone of stonework. Where the presence of salts has caused material detachment on a surface, lichen acids have a large surface area into which they can migrate (surface roughening, pits, alveoli), resulting in further chemical weakening of the matrix/grain interface, and promoting mechanical breakdown.

The role of height on a façade in controlling decay processes and forms merits discussion. In urban areas, buildings are often soiled from street level upwards (due to vehicular pollution), and the height of active decay in buildings has been noted in relation to groundwater and street-level salts (Smith et al. 1992). While soiling, as seen in urban areas, is not present on the structures discussed here, the issue of groundwater being drawn up into blocks at the base of façades is important (the ‘wick effect’, see Goudie 1986). It should be noted, however, that many decorative sandstone features (such as windows) are outside the capillary fringe, and are unaffected by the ‘wick’ effect. That said, where sandstone features do begin at the base of a façade, groundwater moisture becomes an issue and this is reflected in the clustering of lichen at the base of Fig. 7.7. These blocks are damp for long periods of time, and, although decay forms associated with salt attack do not appear to cluster at the base of façades, when drying out occurs crystallization of salts is likely to cause breakdown.

7.3 Discussion—Conservation Implications

Most conservators are very good at identifying the construction history of a building and (within the confines of the available information) investigating previous conservation intervention. However, possibly because they are more likely to come from an architectural tradition, they may be less likely to appreciate the significance of complex environmental histories, their implications for future decay, or their control on the outcomes of conservation actions. This section discusses the conservation implications of complex histories, expanding on the flow chart shown in Fig. 7.13.

When managing stone-built heritage, there is sometimes a fine line between decay and survival (see, e.g., the impact of mis-conservations and misguided restorations, Sects. 7.2.1.3 and 7.2.2.3). In deciding on conservation strategies, an open mind should always been maintained: there are always a range of options or paths through the decision-making process. Because each structure (and perhaps even each stone block within a structure) has a unique stress history, each building should be treated as an individual; there are no rules that can be applied universally. The best approach is not based on a hard and fast set of rules, but, rather, on an understanding of what is needed and on what the act of conservation is setting out to achieve.

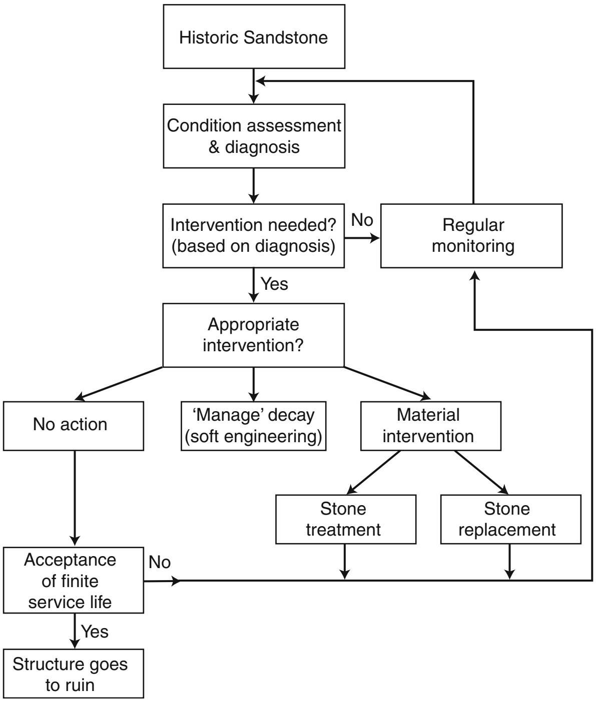

Fig. 7.13 Flow chart illustrating different paths through the conservation decision-making process

> We must… choose between two different patterns of change: change that is in the nature of things, and which sooner or later will have to end with the disappearance of what we would have liked to preserve; or a change that is the product of efficient conservation, that is capable of repeating the creative experience of the past, not in terms of artistic creation, which is definitely precluded, but in terms of scientific imagination and technological innovation (Urbani 1996, p. 449).

While intervention consists of action to maintain, conserve or restore historic sandstone, it should be noted that the most appropriate course of action may be to do nothing. As demonstrated in the case studies, it is better to make no intervention than to make the wrong one, exacerbating decay. Lessons from geomorphology bring with them the 'natural' weathering perspective that stone will inevitably breakdown in response to the environment to which it is exposed: stone decay is, to some extent, irresistible change. Any human intervention could potentially accelerate decay, highlighted by Pope et al. (2002), who encourage conservators to adopt the 'don't touch' attitude of the humanities. Thus, it may be that conservators need to adjust their mindset to the acceptance that natural stone structures have a finite service life. "Time-honoured goals of eternity, stability, and permanence are nowadays increasingly discarded as unreachable. Cultural guardians who once hoped to husband heritage for all time… are learning to accept that things are in perpetual flux" (Lowenthal 2000, p. 20). The marks of age and decay are a part of the historic structures that conservators seek to protect, and perhaps recognition of their transience will produce wiser and more pragmatic care. Ultimately, however, the result of a 'no action' conservation decision, and of the acceptance that a building or monument may have a finite life span, is the complete ruin and disappearance of a historic structure.

The complete loss of a structure may be difficult to accept (and seems to go against the instincts of conservation professionals). Thus, 'managing' decay may be the most appropriate approach to conservation. Allowing an historic sandstone structure to 'grow old gracefully' is a difficult task and the solution is ever elusive (Smith and Přikryl 2007). However, the progressive monitoring of historic sandstone is an essential part of any conservation strategy and this close observation of historic sandstone over time must be the first step in palliative care and successful decay management. Stone surface conditions should be examined at regular intervals so that signs of impending decay and deterioration can be detected. Economic problems arise in long-term monitoring, however; and for all but the most high-profile historic structures, regular monitoring of decay is unlikely to be funded (Searles et al. 1997). That said, the importance of this type of preventative care cannot be stressed enough because it may mean catching decay early so that the problems can be addressed before they become advanced, which would result in the loss of cultural heritage and the need for more drastic action (e.g., stone replacement).

In harmony with the idea of palliative care is 'managed retreat' or 'soft engineering' (Smith and Turkington 2004), where flux is accepted, but the retreat of stone surfaces is carefully managed, so that decay is slowed. Within this school of thought, any direct intervention should be reversible in nature. 'Soft engineering' strategies often include the management of the environment, where the interaction of the surrounding environment with the stone is minimized (Ashley-Smith 1999; Caple 2000; Brimblecombe 1994), or where the environment itself is altered in some way. Crucial to this management of decay is an understanding of the factors that control decay processes, in order that positive (destructive) feedback loops may be 'switched off' and negative (stabilizing) feedback be established. This may be achieved by limiting temperature/humidity and moisture fluctuations; for example, by soft topping (Viles et al. 2002; Viles and Wood 2007), dew-point sensors and heaters (Camuffo 1991), sheltering façades, or hindering moisture and soluble salt ingress (e.g., damp proof courses in the foundation of structures to prevent capillary rise, or water repellants).

In the context of complex stress histories, major stress events have already happened, impacting on the decay pathway of historic structures: natural stone decay systems cannot alter what has happened in the past, just as they cannot anticipate the future (Thornes and Brunsden 1977). Therefore the idea of preventative care is not always applicable. Remedial action, including repairs and restorations, is often needed. Material intervention can essentially be divided into two categories: treatment (e.g., cleaning and consolidation) of stone blocks, and replacement of stone blocks. During intervention new information about the decay may be discovered, which can feed back into the diagnosis and may refine the intervention being undertaken (Searles et al. 1997). Ideally, treatments undertaken should be reversible, compatible with other façade materials (e.g., mortars) and re-treatable (that is, allowing further intervention at a later date). All treatments should be tested as part of a research based approach to stone conservation, individually tailored to the environmental conditions of a specific site. From a lithological point of view, it is likely that surface consolidants will cause stone surface/substrate heterogeneity by altering the character of the near-surface zone, and so encourage rapid decay/surface detachment at a future stage. There are examples of problems with surface treatments from as far back as Schaffer (1932), who warned that consolidants should always be tested: they may only provide stone surfaces with short-term protection from decay.

In some cases, replacement of stone blocks is necessary and the need is obvious, for example, where rapid surface retreat has resulted in the effective disappearance of the original block. Using spatial association analysis (see Turkington and Smith 2004) as a tool can help in deciding whether stone replacement is appropriate:

> Low connectivity [of decay features] suggests that it is safe to remove and replace individual affected blocks. Where connectivity is greater, it may be necessary to remove and replace a large area of wall surrounding the affected stones and treat the area with, for example, a biocide to prevent recurrence (Smith and Přikryl 2007).

A greater degree of connectivity implies a higher degree of environment control on decay (and so altering/controlling the environment in some way may be preferable to stone replacement, which may only provide an aesthetic solution, rather than addressing the stresses that are causing decay). When replacement is the favourable option, the conservator must ensure that the new stone is compatible with the original monument materials (i.e., not exacerbate decay), and that the stone is suitable for long-term survival in the environment in which it is being placed. Knowledge of the performance of replacement stone in specific environments can be gained by tailored simulation experiments. If either of these two criteria is overlooked, accelerated decay can occur, either of the original or replacement stone. For example, Fig. 7.9 showed the surface of replacement stone in the cloister of Iona Abbey (restoration carried out in 1959). This stone is decaying much faster than the original stone (which exhibits a stable surface), through mechanisms of granular dissaggregation and scaling of the stone surface, because of its unsuitability to the aggressive maritime environment of the Scottish Western Isles.

7.4 Conclusions

Sandstone is a widely used historic building material that has aesthetic appeal and is relatively durable. However, like all porous media, sandstone is susceptible to exploitative environmental decay processes, and, especially over the long timescales dealt with in this study, age and decay are becoming an increasing concern in sandstone-built heritage. The factors controlling the performance of stone over long periods of time (in the case of these structures, hundreds of years) are very complex, depending on the interaction of environment, history and stone character. Descriptions of histories and their impact on stone illustrate how stone strength is likely to have declined over the centuries, conditioning the stone's response to the present-day environment.

The case studies are both situated in exposed maritime environments. As a result, decay forms in evidence at Bonamargy Friary and Iona Abbey are broadly similar. However, decay maps have illustrated that over a single façade or feature there is variable response of historic sandstone blocks to their present-day environment. One important way of explaining variable response (why some blocks decay whilst others survive) is to take into account different complex stress histories, where no two blocks will have experienced exactly the same number, frequency or magnitude of stress events, encouraging divergent behaviour over time. This divergent, individual, behaviour of blocks suggests that targeted, research-based, conservation tailored to specific blocks in specific environments (rather than all-encompassing conservation strategies) is necessary for the future management and survival of stone-built heritage. In the context of heritage, understanding why sandstones survive is as important as understanding why they decay. An appreciation of this can inform intervention and will help in the choice of new and replacement stone that can avoid the life of stone-built heritage being curtailed by non-targeted conservation strategies and uninformed decision-making.

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Chapter 8
The City of Dresden in the Mirror of its Building Stones: Utilization of Natural Stone at Façades in the Course of Time

Heiner Siedel

8.1 Introduction

Natural stone is an old, traditional building material. Wherever solid rocks with appropriate technical properties appear at the Earth's surface, they have been used for building purposes. The building stones used in villages and cities often reflect the regional geology of the surrounding area (e.g., Frangipane 2004; Franzen and Mirwald 2004; and many others). In the north of Germany where solid rocks are lacking and the geology is dominated by the Quaternary with unconsolidated rocks like gravel, sand and clay, churches and town halls were built of bricks in the Gothic period. At the same time, craftsmen made use of sandstones in Saxony and limestones in Thuringia to erect the same kind of buildings. Transport was a limiting factor for the use of building stones far away from the rock deposits in ancient times. The situation was changing only in the middle of the 19th century with the development of a better infrastructure with roads and railways and improved means of transport.

Even if the geographical situation of a city and the regional geology played an important role in the past, the use of building stones at façades has also been influenced by changing political, economical and technical conditions in the course of time.

Within this framework, a systematic record of kind and frequency of building stones at the façades of one particular city seems to be attractive. Thus, the relevant factors that set the tone for their use can be discussed in more detail against a definite natural and historical background. Comparable studies with a statistical approach were already carried out in Germany for Munich/Bavaria (Grimm and Schwarz

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1985) and recently for Leipzig/Saxony (Raum and Siedel 2008). The recording of building stones used at façades in the city of Dresden aims at the broadening of knowledge of both the history of local important building stones and technical aspects of their application and weathering durability.

8.2 A Short History of Dresden

Dresden is situated at the very south in the east of Germany. It was first mentioned in the year 1206 and first called a town in 1216. In 1485, Dresden became the residence of the Saxonian rulers and some decades later, in 1547, the capital of the Protestant electorate of Saxony under the elector Moritz. The most famous buildings of Dresden (like the Zwinger or the Church of Our Lady) were erected in the 18th century in Baroque style. In this period, not only churches and palaces, but also a lot of living houses in the city centre were built. They characterized the structure of the old town for more than 200 years.

The fortress walls around the old town were razed to the ground at the beginning of the 19th century. This opened the chance for a further development and expansion of the city. Lots of new living houses were built particularly in the period of the last third of the 19th century when many industrial firms were established in Germany. During and after World War I only a few buildings were erected because of the bad economic situation.

Dresden was heavily destroyed in the last months of World War II by allied bomb attacks on February 13th and 14th, 1945. The historic, Baroque city centre was nearly totally ruined. The world-famous Zwinger was rebuilt within the first two decades after the war (finished in 1964), but many other important historical buildings like the opera house, the Residence Castle or the Church of Our Lady remained ruins for decades. The remnants of many Baroque façades were blown up by the communist rulers after 1945 to make space for new living houses and to build a new "socialist city". Even in 1963, nearly twenty years after the war, the ruin of the last Gothic building in the city centre, the Church of St. Sophie, was destroyed for this reason. Planning and construction of buildings during the years of the German Democratic Republic (1949–1990) were often dominated by a poor economy and ideological thinking.

After political changes and the reunification in 1990, many new office blocks and living houses were constructed in the East German cities and in Dresden as well. Many of them are made of concrete, glass and steel. However, façade panels of natural stone have frequently been used to make the face of buildings more attractive. Better economical and technical conditions also allowed the restoration and reconstruction of many important historical buildings in the city centre. 15,000 m^3 of sandstone were quarried in the Elbe valley south-west of Dresden to re-erect the Church of Our Lady, which was finished in 2005. Lots of living houses have been built around the church in the last few years. All are modern buildings, most of them with Baroque façades reconstructed by the use of traditional construction materials like stucco or sandstone.

8.3 Geological Setting and Building Stone Quarrying

Dresden is situated in the Elbe Zone between the Lausitz Anticline (Lusatia) with mainly Cadomian granitoids (granodiorites and granites), intersected by dark dyke rocks (lamprophyres) in the east and the Erzgebirge Anticline with Variscan metamorphic rocks and granites in the west. The Variscan igneous complex of the Meissen Massif with mainly granitoid rocks directly adjoins to the north.

The Cretaceous sediment basin of the Elbe Zone consists of up to several hundred metres thick layers of clays, marlstones and sandstones. The city itself lies on Upper Cretaceous marlstones, covered by younger Quaternary sediments. Some 20 km to the south in the Elbe river valley, Upper Cretaceous outcroppings form the so-called "Saxonian Switzerland", a sandstone area with peculiar geomorphological forms.

The geology of the surrounding area offers several rocks that can be used as building stones. Archaeological excavations in Dresden proved the early use of the local marlstones for masonry. Besides, also sandstone from the Elbe valley was applied for carved elements like door and window jambs, corner stones and columns in the Middle Ages. It has been quarried at least since the early 13th century. Later it became the most frequently used building material in Dresden for centuries. The conditions of supply were convenient because the river Elbe allowed transport by ship. For construction purposes, a general differentiation between a medium to coarse-grained, silica-bound "Posta sandstone" and a medium to fine-grained, argillaceous "Cotta sandstone", named after two important quarry regions, is made. Within both groups the petrographic and weathering properties scatter over a wide range (Götze and Siedel 2004).

Igneous rocks of the Meissen Massif and from Lusatia were of local importance only until the middle of the 19th century. Lots of quarries developed in these regions with the growing demand for building stones in the period of industrialization after 1830. They were producing dimension stones as well as stone chippings and cubes for road construction. Building stones for bridges and grit for track bed courses were needed during the construction of a railway line from Görlitz (Lusatia) to Dresden 1845–1846 and came from nearby quarries in the granodiorite. This railway line to Lusatia facilitated a faster and cheaper transport of stone to Dresden and to other regions, thus encouraging the developing quarry industry.

8.4 Methods

The recording of natural stone at façades was limited to the municipal district Old Town (Altstadt) which contains the historical city centre (Fig. 8.1). Three hundred and fourteen buildings with natural stone were recorded in the selected area (only from the front side, not from the back). Natural stone used in the interior was neglected. Data collection was carried out with respect to the age of the building as

Fig. 8.1 Historical city centre of Dresden with (from the *left* to the *right*) the Church of Our Lady (1738), the Old Parliament House (Ständehaus 1906), the tower of the New Town Hall (1910), the Cathedral (1755) and the Residence Castle (15th–20th century)

well as to the architectural elements the stone was used for. Since different stone materials have been used for different elements in the same building in some cases, the number of recorded occurrences can be higher than the number of buildings. The following architectural elements were recorded: bases, façade faces (panels on new buildings; cornices, ornaments, reliefs and ashlars on historic buildings), window jambs/sills/lintels, portals and pillars/columns.

The lithological determination of the building stones was carried out by visual observations as precisely as possible. The well-known rocks from the region (Cotta and Posta sandstone, granodiorite and lamprophyre from Lusatia, granite from Meissen) could be assigned to certain quarry regions. Stones from other parts of Germany or from abroad could not be determined in detail in many cases. They were recorded in more general petrographic categories (e.g., granite, gabbro, sandstone, limestone etc.). The age of the historic buildings was taken from the literature (e.g., Dehio 1996) or from inscriptions on the façade. The age of new buildings (after 1990) could be easily ascertained by our observations. Buildings without any detailed information concerning their age (mainly living houses) could be roughly categorized by stylistic criteria and the age of similar buildings in the same quarter or were excluded from the discussion of building ages if no information could be obtained at all.

To evaluate the use of distinct building stones in history, the recorded buildings were classified in time periods. The time periods were established in accordance with historical periods that characterized the development of the city (Fig. 8.2). Only a few buildings are left from the Renaissance period (before 1700). The most

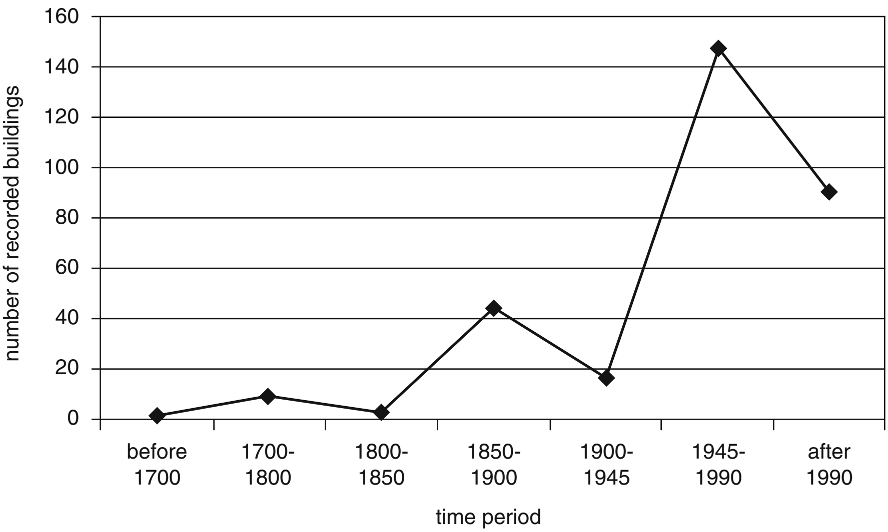

Fig. 8.2 Classification of the recorded buildings in time periods according to their building ages

famous buildings are from the 18th century, when the electors of Saxony were also Kings of Poland and Dresden became a royal seat and an important city in Europe. Lots of living houses from this time were destroyed in World War II. Only a few churches, palaces and other representative buildings in Baroque style have been restored after the war. Thus, the number of recorded buildings for this important period is rather small. A small number of buildings were also recorded for the period between 1800 and 1850, whereas a higher number could be found for the second half of the 19th century. Especially the last third of the 19th century was characterized by the establishment of many industrial firms and enormous construction activities. Many living houses from this period at the edge of the city centre survived the bomb attacks in 1945. Most of the recorded buildings are from the period between 1945 and 1990, the time of the German Democratic Republic, including the reconstruction of main parts of the city centre in the first three decades after the war. Building activities after political changes in 1990 are still in progress, and the number of new buildings is growing.

8.5 Results and Discussion

8.5.1 Recorded Natural Stones and Frequency of the Main Petrographic Groups

Natural stones found at façades in the investigated area are presented in Table 8.1. They come from the surroundings of Dresden as well as from other places in

Table 8.1 Building stones recorded on buildings within the municipal district of Old Town in Dresden

Rock group	Building stones recorded in Dresden, Old Town
Sedimentary rocks	Posta sandstone, Elbe valley Cotta sandstone, Elbe valley Other sandstones (e.g., Silesian sandstone, Poland; Hořice sandstone, Czech Republic; Schönbrunn sandstone, Franconia/Germany, …) Jurassic limestone, South-Germany Muschelkalk (Mesozoic limestone), Germany Anröchte limestone, North Rhine-Westphalia/Germany Saalburg limestone, Thuringia/Germany Other unknown limestone
Igneous rocks	Granodiorite, Lusatia Granite, Meissen Massif Granite-porphyry, Beucha/Saxony Other granitoid rocks of unknown origin Lamprophyre, Lusatia Gabbro (unknown origin) Basaltic lava 'Basaltina', Italy Rhyolithe tuff, Chemnitz/Saxony
Metamorphic rocks	Theuma spotted slate, Saxony Gneiss (unknown origin) Migmatite (unknown origin)

Germany or from abroad. The number of different sorts of natural stones is rather low in Dresden, compared to other cities like Leipzig (Raum and Siedel 2008).

With regard to the frequency of use (Fig. 8.3), sedimentary rocks are dominant, whereas metamorphic rocks are rare. Sandstones are the most frequent sedimentary rocks (64%), limestones were only found in a few cases (2%). One third of the recorded occurrences are igneous rocks. Among them, plutonic rocks (including also dyke rocks) are absolutely dominant. This pattern is comparable to the results obtained in the city centre of Leipzig (sedimentary rocks 65%, igneous rocks 26%, pyroclasic rocks 7%, metamorphic rocks 2%; Raum and Siedel 2008), even though the regional geology of the surroundings is different. Sedimentary rocks can be more easily quarried and carved than the dense, hard rocks of metamorphic or igneous origin. For this reason, they have been the favourite building stones from the very beginning wherever they were available.

8.5.2 Use of Natural Stones for Distinct Building Purposes

Figure 8.4 shows the use of the different rock groups for particular architectural elements. Sedimentary rocks (mainly sandstones, as can be seen from Fig. 8.3) have been used for all building purposes. Igneous rocks have mainly been applied as building stones for the bases of buildings and to a lower extent also for façade faces, portals and columns. On new buildings, granite or gabbro panels in the base

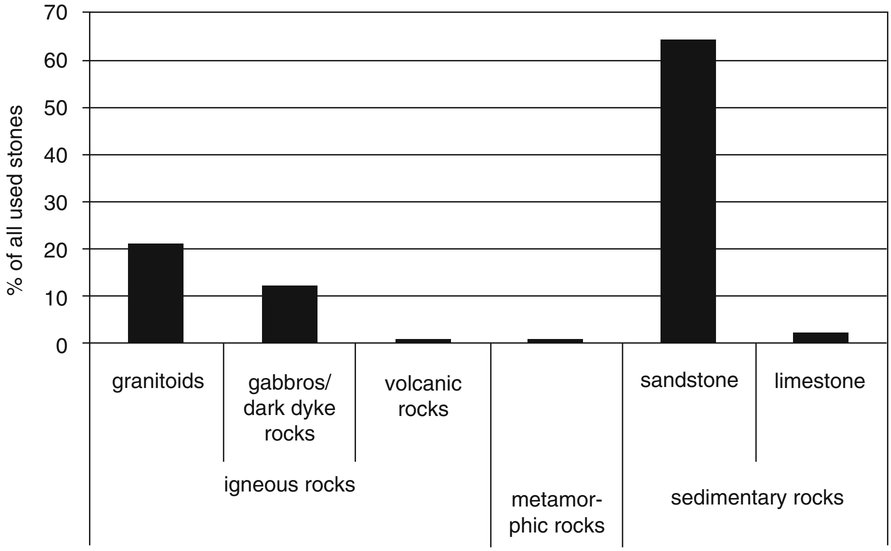

Fig. 8.3 Frequency of use of building stones from different rock groups, related to the total number of all recorded occurrences on buildings in Dresden, Old Town

are sometimes the only natural stones used. This makes sense in the light of their technical properties. Since they have crystalline textures with very low pore space, water cannot easily be transported through their volume by capillary action. They are dense and resistant to both frost and salt attack. Moisture from splash water

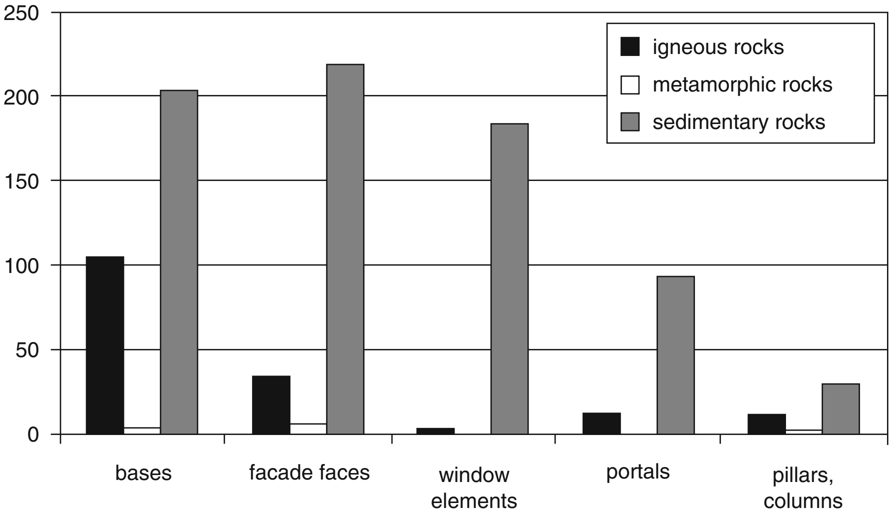

Fig. 8.4 Number of occurrences of building stones from different rock groups in distinct architectural elements on façades of buildings in Dresden, Old Town

Fig. 8.5 Granodiorite from Lusatia, used in the bases of the building of the Academy of Fine Arts in Dresden, is in a stable condition after 115 years of exposure to splash water

as well as from the ground accumulates at the bases of buildings. Igneous rocks used in this position are resistant to weathering and can avoid capillary transport of water to the upper parts of the façade. The example of the granodiorite from Lusatia which has been utilized for construction in Dresden for more than 140 years shows the good durability of this kind of natural stone. Apart from surface blackening and minor material loss near the surface it is normally in a stable condition (Fig. 8.5, cf. Table 8.2).

Sandstone has also been used for bases to a large extent. The dominant building stone in this position is Posta sandstone. It has been utilized more than twice as much as Cotta sandstone (Fig. 8.6). This uneven distribution of the two regional important building sandstones can be explained by their petrography and the resulting technical properties. Posta sandstone is a medium to coarse-grained quartz arenite with siliceous intergrain cement and high compressive strength (Fig. 8.7, Table 8.2). Although it has high porosity and good capillary suction, its resistance to frost

Table 8.2 Technical properties of sandstones from the Elbe valley and of granodiorite from Lusatia

	Cotta sandstone	Posta sandstone	granodiorite, Lusatia
Total porosity [vol.%]	22.8	21.8	1.0–1.8
Total water uptake [wt.%]	8.9	7.6	0.26
Compressive strength [MPa]	40	55	150–220

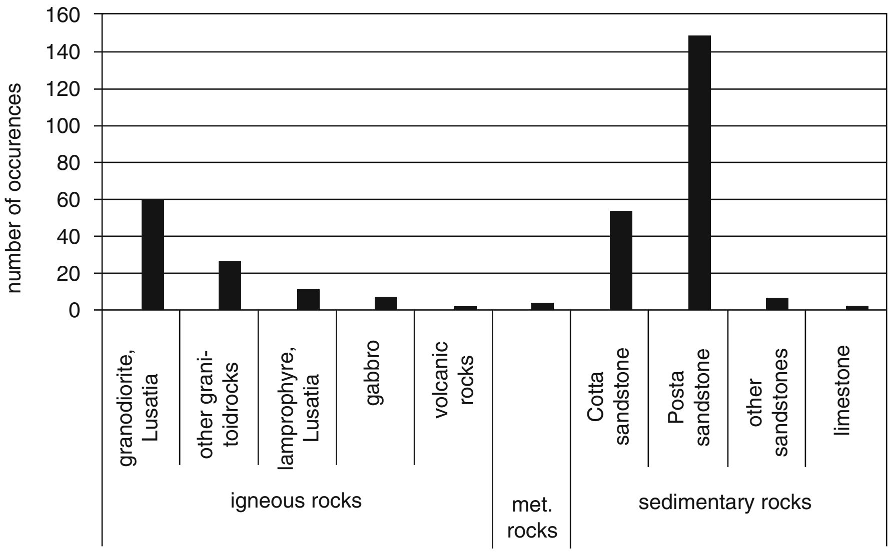

Fig. 8.6 Number of occurrences of different building stones in the bases of buildings in Dresden, Old Town

and salt attack is excellent. Cotta sandstone is a fine to medium-grained sandstone with up to 5% clay minerals (kaolinite, illite). Intergrain cement is mainly siliceous. Pore filling cements consisting of clay minerals occur in some places along the bedding planes (Fig. 8.8). They reduce the compressive strength (Table 8.2) and represent weak zones in the texture, being responsible for a lower frost and salt resistance (Siedel 2007). Differences in long-term behaviour of Cotta and Posta sandstone could be found in the bases of the recorded buildings. Apart from blackening of the surface, Posta sandstone is normally in a good condition. Cotta sandstone in bases

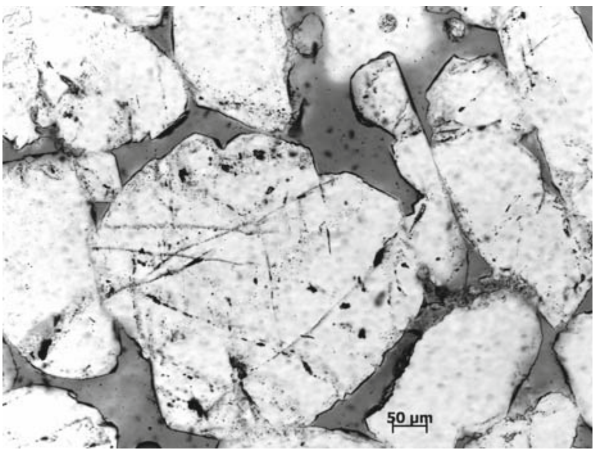

Fig. 8.7 Optical micrograph of Posta sandstone from the Elbe river valley. Thin section, plane polarized light, Nicols parallel

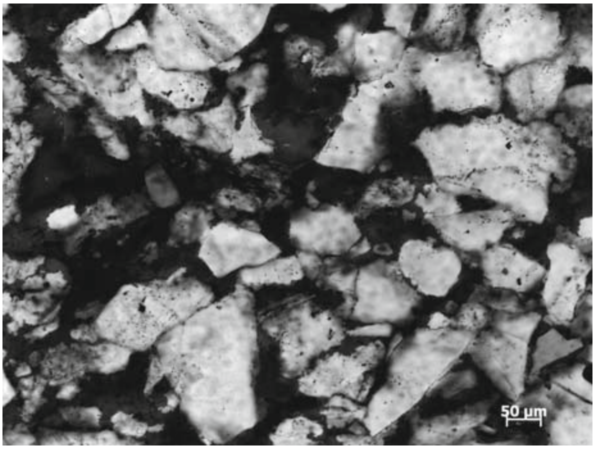

Fig. 8.8 Optical micrograph of Cotta sandstone from the Elbe river valley. Thin section, plane polarized light, Nicols parallel

often decayed (Fig. 8.9) and has been replaced by Posta sandstone on many historical buildings. On the basis of this experience, Posta sandstone became the favourite building sandstone for bases of new-built constructions after 1900 (Fig. 8.10). Only in the period after World War II was Cotta sandstone utilized again for bases to a certain extent. This might have been caused by delivery problems in the years of the German Democratic Republic when the production of natural stone was low. Bases of pillars covered with panels of Cotta sandstone on buildings of the 1960s

Fig. 8.9 Cotta sandstone in the base of a building from the late 19th century (Jahnstraße). The decayed sandstone was partially covered with repair mortars

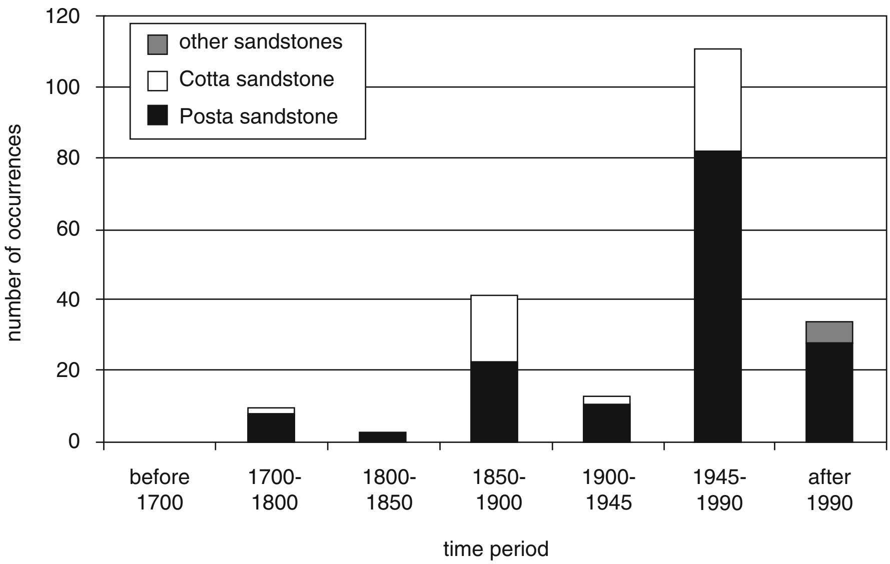

Fig. 8.10 Utilization of different sandstones for the bases of buildings in Dresden, Old Town, in the course of time

(Wilsdruffer Straße) were already in a bad condition some decades later (Fig. 8.11) and had to be replaced. Other sandstones (often from Silesia, Poland) have sometimes been used for base panels in Dresden after 1990. They are similar to Posta sandstone with regard to their weathering behaviour and were additionally treated with water repellents in some cases.

Cotta sandstone has been frequently used for structuring of both façades built of mixed construction materials like brick and natural stone and plastered façades. The favourite use of Cotta sandstone for façade elements like cornices, windows and ornaments is exemplarily demonstrated for window elements (window sills, jambs and lintels) in Fig. 8.12. The fine-grained, argillaceous sandstone can be easily chiselled and has therefore been the favourite material for ornaments, moulded window or door jambs and for sculptures as well. It has also been utilized together with Posta sandstone for the reconstruction of Baroque façades in the historic city centre around the Church of Our Lady (Frauenkirche/Neumarkt) after 2005.

8.5.3 Utilization of Natural Stone in Dresden in History and Today

The utilization of different stone materials in Dresden over the course of time is displayed in Figs. 8.13 and 8.14, summarizing all recorded occurrences of natural stones on buildings for the distinct time periods established above (see Sect. 8.4). For

Fig. 8.11 Cotta sandstone used for cladding of pillars on a building from the middle of the 1960s (Wilsdruffer Straße)

a direct comparison of the time periods, the number of occurrences of each recorded type of building stone was related to the total number of buildings recorded for each period and is given in percent. In many cases, more than one type of building stone was used on a building, e.g., Cotta sandstone for windows and Posta sandstone for bases. Therefore, the sum of percentages for one period can exceed 100. Because of the different number of buildings recorded for each time period (cf. Fig. 8.2), results are not significant in terms of statistics for every period. This is especially true for the time before 1850. By consideration of additional observations in other municipal districts of Dresden and information obtained from literature, however, even a few recordings can show the main trend. Details for each period are discussed below.

8.5.3.1 From the Beginning to the 17th Century

Only little information about building stones could be obtained for the early period of Dresden's history by recording the façades in the selected area. Most of the

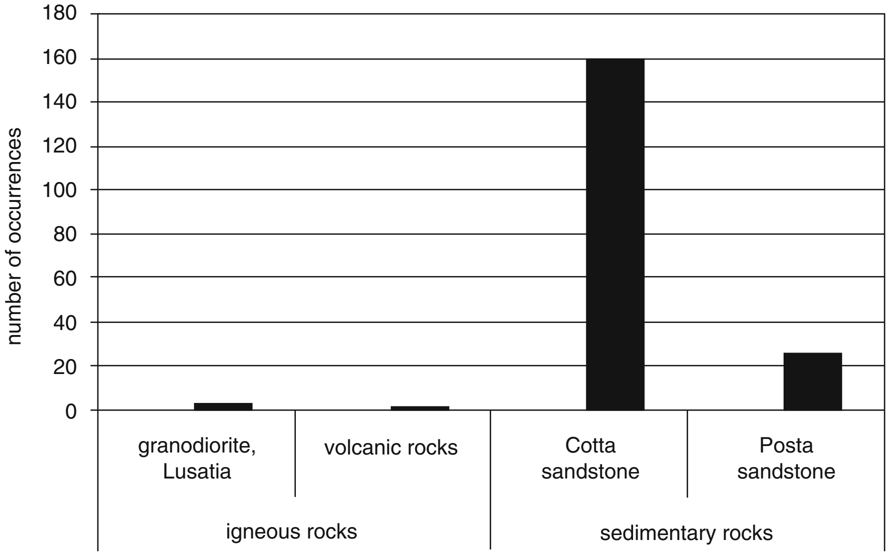

Fig. 8.12 Number of occurrences of different building stones in window jambs and lintels on façades of Dresden, Old Town

buildings of this period have been destroyed or thoroughly reconstructed. Remnants of the original building structures and materials can be found in the interior, in cellars, or have been excavated in the course of archaeological investigations. Most of

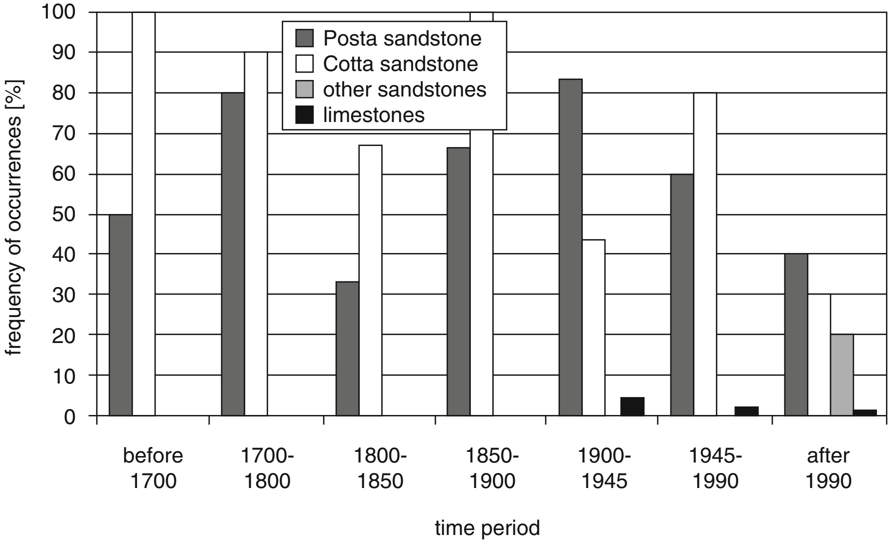

Fig. 8.13 Percentage of façades recorded in Dresden, Old Town, with the occurence of different sedimentary rocks used as building stones in the course of time (related to the total number of buildings recorded for every time period)

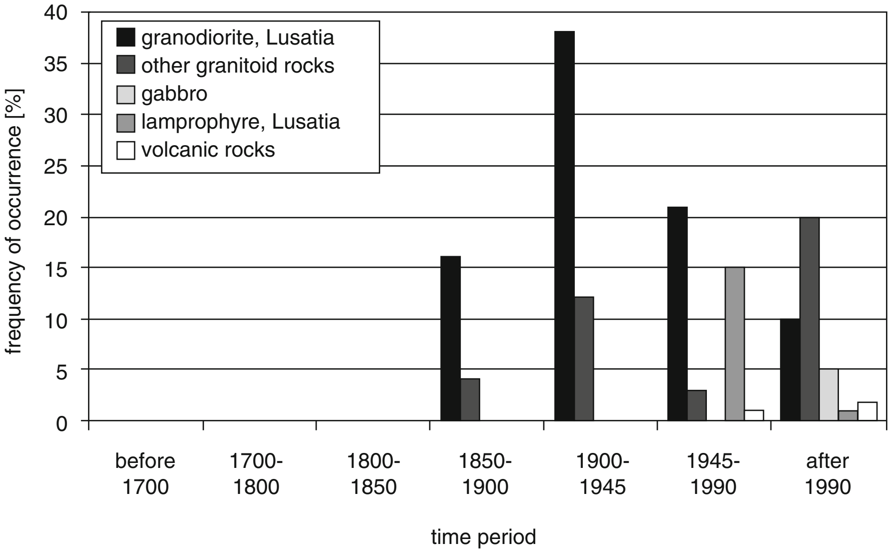

Fig. 8.14 Percentage of façades recorded in Dresden, Old Town, with the occurence of different igneous rocks used as building stones in the course of time (related to the total number of buildings recorded for every time period)

the living houses were half-timbered constructions with brickwork or stonework bases. Beside the local Cretaceous marlstones, sandstones of the same age from the area south of Dresden and from the Elbe valley around the town of Pirna were utilized for representative buildings like churches or the Residence Castle. In the Middle Ages, sandstone was applied only for carved elements like door and window jambs, corner stones and columns, whereas local marlstones were utilized for masonry. Cotta sandstone was never recorded on buildings until 1470. Posta sandstone might have been quarried for building purposes already in the 12th century (Beeger and Siedel 2007). A greater demand for building and ornamental sandstones developed since the first half of the 16th century when Dresden was extended as a prestigious residence city in Renaissance style. Cretaceous sandstone was the only natural stone used for building purposes in this period.

8.5.3.2 18th and First Half of the 19th Century

Famous buildings from the 18th century like the Zwinger, the Church of Our Lady or the Cathedral established the reputation of Dresden as a Baroque city. Churches, palaces and living houses were built of sandstone or brick masonry. Architectural surfaces were often painted or covered by plaster. Structuring architectural elements like cornices, window jambs and lintels and sometimes ornaments were made of sandstone. Sandstone from the Elbe valley is the only natural stone recorded on façades from this period.

After 1800, some constructions in classical style like the building of the guards of the Residence Castle (1830–1832, planned by the architect Friedrich Schinkel) were built entirely of Cretaceous sandstone from the Elbe valley.

8.5.3.3 1850–1900

The second half of the 19th century is characterized by the fast development of industry and infrastructure and by many new living houses built mainly in the last third of the century. The façades with mixtures of construction materials like clinker, plaster, stucco and stone elements contain a lot of Cotta and Posta sandstone. The local sandstone material can also be found in the bases of the constructions. Granodiorite from Lusatia occurs for first time on constructions in Dresden from this period. It is mainly found in bases of big public buildings like the main railway station, the building of the court of justice and the police headquarters. Other granitoid rocks like Scandinavian granite or granite from Meissen are rare. At the same time thousands of tons of granodiorite and lamprophyre from Lusatia came to Dresden as paving and kerbstones for road construction purposes. Together with the red granite from Meissen they were also frequently applied for pedestals of statues after 1850.

8.5.3.4 1900–1945

Some of the recorded buildings from this period were erected before World War I and reflect the same principles of utilization of natural stone as used in the late 19th century. Again, granodiorite from Lusatia was only used for bases of buildings, whereas façade elements were made of the sandstones from the Elbe valley. Mesozoic limestone (Muschelkalk) was only found once in the portal zone of the building of a health insurance company. At the same time, this limestone was a frequently used construction material in cities like Leipzig (Raum and Siedel 2008) or Berlin.

After the first World War only few buildings were erected until World War II. Among them is the German Museum for Hygiene (1930–1932). The portal zone as well as window jambs, lintels and sills of the concrete construction are made of Lusatian granodiorite.

8.5.3.5 1945–1990

After the bomb attacks in February 1945, large areas of the old town of Dresden were ruined. The urgent demand for living houses in the destroyed city as well as the plans of the communist rulers to build a new “socialist city” led to an architectural design for the city centre that mainly ignored the old structure with narrow streets that had grown up over centuries. Lots of ruins of Baroque living houses were blown up. Other, more famous buildings like the opera house or the Residence Castle remained ruins until the eighties or nineties because there was no money to reconstruct them.

Fig. 8.15 Façade of a living house (Grunaer Straße) built at the beginning of the 1950s, restored after 1990. Posta sandstone is used for the ground floor, Cotta sandstone for upper façade faces, reliefs, inscriptions and windows

The construction of modern living houses in Dresden after World War II can be divided into several periods: In the fifties, the buildings in the very city centre around the central market place (Altmarkt) and along the big street used for parades (Wilsdruffer Straße/Grunaer Straße) were erected with bricks from destroyed houses and plastered. Natural stone (mainly sandstone) was frequently used in this period for bases (Posta sandstone, sometimes granodiorite from Lusatia), windows and portals (Cotta and Posta sandstone) as well as ornaments (Cotta and Posta sandstone, Fig. 8.15). In the sixties, natural stone panels were utilized for cladding of concrete constructions in the city centre (Fig. 8.16). Large areas with many blocks of living houses from the sixties and seventies at the edge of the city centre were built of concrete without any use of natural stone. In the late eighties, a few new living houses situated near the historic centre, with shops on the ground floor, got a thrifty cladding with sandstone from the Elbe valley as well as lamprophyre from Lusatia.

During the period of the German Democratic Republic (GDR) natural stone quarrying and utilization was limited for economical reasons. There was no money for the opening of new quarries or for import of natural stone from abroad. The natural stone used for construction of new buildings in Dresden in this period came from the Elbe valley (sandstone), from Lusatia (granodiorite, lamprophyre) and from Meissen (granite). These quarries–among a few others–also supplied building and decoration stone for other cities in the GDR. Moreover, they provided stone for restoration and reconstruction of historic buildings after the war. Since these materials have been traditionally used in Dresden for years, the frequent use of

Fig. 8.16 Façade of a building from 1963 (Wilsdruffer Straße), covered with cladding of Cotta sandstone (pillars) and lamprophyre from Lusatia (black panels)

the same, limited number of sorts does not come to attention. Only in a few cases, other stones like coloured Devonian limestone from Thuringia, spotted slate from Theuma (West Saxony) or granite from the former Soviet Union were applied for façade cladding.

8.5.3.6 After 1990

The political changes in the years 1989–1990 opened new chances for the utilization of natural stone in Dresden. Much money was invested to restore historic monuments and to rebuild parts of the city after the reunification of Germany. New buildings have been erected for business and trade, many of them by the use of natural stone for façade cladding. Sandstone from the Elbe valley has been constantly applied also for panels on buildings erected in the years after 1990. In addition, sandstones from Poland (Silesia) and the Czech Republic as well as from other parts of Germany have been utilized. The number of buildings with other sandstones is still growing. This might be explained by the lower prices for imported materials. However, it is a matter of fact that the appearance of the imported Polish and Czech sandstones is very similar at first sight to that of Cretaceous sandstones from the Elbe valley. Up to now, façades with red or green coloured sandstones are lacking in the city centre of Dresden. The dominant colours are grey, yellow or light brown, thus maintaining the traditional appearance of sandstone façades in the city. Only original sandstone from the Elbe valley has been used for the reconstruction of Baroque façades around the Church of Our Lady which itself was rebuilt from Posta sandstone.

Plutonic rocks have been frequently used as base panels on new buildings, in some cases also for the whole façade or parts of it. Even if granodiorite from Lusatia was still utilized in the early nineties, it has nearly totally lost its importance today. The same is true for the lamprophyre from Lusatia. Plutonic rocks come from all over Europe as well as from overseas today and are mainly judged by their price. Limestones from Germany and from abroad are still rare on façades in Dresden.

8.6 Conclusions

The recording of natural stones on façades in Dresden has demonstrated the great influence of regional geology on their utilization. From the Middle Ages until the middle of the 19th century, Cretaceous sandstone from the Elbe valley was the one and only natural stone used for building purposes, apart from local Cretaceous marlstones in the early period. The geographical situation of the sandstone quarries some 20 km south of the city along the river Elbe favoured the transport by ship to Dresden as well as to other destinations. Until today, Posta and Cotta sandstone have remained important building stones for the city of Dresden both for restoration measures and modern constructions.

The improvement of transport and quarry technology in the second half of the 19th century only slightly increased the number of building stones utilized in Dresden. Granodiorite from Lusatia has been primarily used for bases of buildings since that time because of its appropriate technical properties. Dark dyke rocks (lamprophyres) from the same area have been applied for pavement and pedestals since the last third of the 19th century and became more important as dimension stone for façade cladding after World War II. Red granites from Meissen were occasionally utilized as building stones for bases and columns and also for pavements.

Since the surroundings of Dresden supplied appropriate stone material for different construction purposes, only a limited number of local building stones left their mark on the façades of the city for centuries or at least for decades. This is not only a result of the local situation, but also of the good technical quality of these building stones. As we know from other places, local important building stones often lost their importance in the course of time, and the quarries closed down as soon as material of better technical quality was available (Raum and Siedel 2008; Grimm and Schwarz 1985).

The last two decades after German reunification in 1990 have been characterized by an increasing number of different natural stones used on façades in the city of Dresden. The same tendency could be observed for the city of Leipzig (Raum and Siedel 2008) where the variety of new building stones is still greater. Even if the global market offers numerous sorts of building stones today, the traditional trend to use mainly yellow to grey sandstone for façade cladding in Dresden seems to be constant at least for the city centre.

Recording natural stones used on façades in the course of time can help to throw light on the relationship between architecture, construction materials and natural as well as political and economical conditions. Furthermore, it can give useful hints towards the technical quality and the long term behaviour of different building stones.

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Chapter 9
Determination of Source Areas of Natural Stones: A Methodology Approach Applied to Impure Crystalline Limestones

Aneta Šťastná and Richard Přikryl

9.1 Introduction

Determination of the proper source of a natural stone used in monuments is required for numerous reasons including detection of forgeries, assessment of authenticity, correct dating of the objects, determination of past trade patterns, and an understanding of changing aesthetic tastes. The provenancing of archaeological marbles requires application of the correct analytical techniques which should match the following general requirements: (1) non-destructivity (or very low destructivity) so that samples are not destroyed during the measurement (and only a modicum of the material is sufficient for the analysis); (2) an extensive exploration of the technique, in terms of provenance studies (with knowledge of the limitations and strong points, and sufficient databases of characteristics for juxtaposition); (3) method suitability in terms of an unambiguous determination of different marble types (i.e., to find feature(s) which differ significantly in various types and quarries, respectively, but not in the same sample); and (4) effortlessness, speed, and relatively low cost of the measurement (this is a great advantage in the case of widespread measurement availability in diverse laboratories universally. The detailed characterization of marbles from historic quarries presents the essential first step in an attempt to determine the provenance of artefacts. The examination of stones from the various quarry sources means the beneficial independence of the amount of sampled material but also represents a difficult task for a number of reasons: (1) the rock mass exhibits significant variations in properties at individual localities due to e.g., compositional variation, secondary veining, and/or various intensities of deformation on a dm-m scale; (2) stone coming from different localities may exhibit similar macroscopic and/or microscopic characteristics; and (3) intensive international trade since

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antiquity means that highly valued stone varieties were transported over large distances. To overcome the all aforementioned difficulties, various observational and analytical techniques have been suggested over the past few decades.

9.2 Development and Types of Marble Provenancing Techniques

9.2.1 Macroscopic Observation

In the past the first approach to the characterization of decorative marbles was based mainly upon stylistic criteria and on traditional identification by a simple inspection, using the unaided eye or magnifying glass (Kokkorou-Alevras et al. 1995). This empirical method could not reliably identify the provenance in many cases, and because of this, modern scientific methods were introduced and applied. Macroscopic methods based on marble objects (e.g., slabs) are less frequently employed in such investigations. Image analysis demonstrates this kind of application, e.g., in the computer-assisted colour assessment of variegated marbles (Foster et al. 1992). Recently used non-destructive spectrophotometric colour testing, by means of a portable apparatus, characterizes white and grey marbles from the artistic-aesthetic points of view, and can also facilitate the search for the sources with the aid of colour parameters, such as the Whiteness Index in some cases (Zezza 1999).

9.2.2 Microscopic Characterization and Systematic Analytical Approach

The microscopic examination of thin marble sections by conventional optical microscopy is probably the oldest scientific method (Lepsius 1890). Discriminating petrographic characteristics such as the types of accessory minerals, micro-fabric, grain size, etc. can be obtained by means of an optical microscope. Electron microanalytical techniques are used today as a complementary method to identify minerals' composition (e.g., Capedri and Venturelli 2004), but its ultimate application consists of the study of the weathered surfaces (e.g., Doehne et al. 1992; Heller and Herz 1995) and encrustation (e.g., Maravelaki-Kalaitzaki 2005). The quantitative microstructural analysis represents a further effective complementary method for source determination of marbles. In addition to the determination of grain size (mean and maximum grain size) applied by previous workers (e.g., Moens et al. 1992; Ramseyer et al. 1992), petrographic image analysis established other compositional discrimination parameters such as axial difference, perimeter/surface ratio, shape factor, and shape-specific PARIS-factor (Schmid et al. 1999a, b). They have proven the beneficial independence of the sample orientation, with respect to the reference quarry, on the studied fabric parameters; and this is approximately true for marbles with a granoblastic microstructure. The combination of the quantitative fabric analysis with the cathodoluminescence study allows the discrimination of white marbles in cases where the cathodomicrofacies is common to more than one area. However, data and comparative studies available from other areas, apart from the explored Mediterranean basin, are still absent.

9.2.3 Mineralogical-Geochemical and Physical Analyses

Identification and semi-quantification of the minerals present in powdered rocks is resolved by X-ray diffractometry. In the case of marbles, their insoluble residues obtained by dilution of the carbonate with 1M HCl are employed for the assessment. This method yields good results if the mineral content exhibits low variability within a quarry (Antonelli et al. 2002). However, the need for large amounts of material for analysis of insoluble residues (a calcitic sample can lose up to 99% of its volume during leaching) particularly disqualifies this method for artefacts from which only minute specimens can be obtained. Up until now, the mineralogical-petrographic characteristics of marbles obtained by optical microscopy and X-ray diffractometry (with a combination of other techniques) was one of the most widely used sourcing methods (e.g., Gorgoni et al. 1992; Lapuente 1995; Lazzarini et al. 1995, 2002; Lazzarini and Turi 1999; Antonelli et al. 2003; Luke et al. 2006).

Conventional optical microscopy of thin-sections has recently been augmented by use of a cathodoluminescence (CL) study. The different colours of the luminescence of marbles depends on impurities hosted in the crystal or on lattice defects of the carbonate minerals (manganese is the principal activator) (Machel 2000). Barbin et al. (1992a) subdivided white marbles into three major families of cathodomicrofacies: orange, and blue (both for calcitic marbles), and red (dolomitic marbles). Also quantitative CL characteristics such as the intensity and distribution of the luminescence, by means of scanning electron microscopy, were established (e.g., Blanc et al. 2002; Lapuente and Blanc 2002). The use of cathodoluminescence as an accessory to C-O stable isotopes, and eventually to petrographic characteristics, was confirmed to be very discriminating in the provenance determination of white marbles (e.g., Barbin et al. 1992b; Barbin 1999; Herrmann and Barbin 1993; Lapuente et al. 2000, 2002; Mentzos et al. 2002).

When considering laboratory analyses of a rock's chemistry determination, at first only elemental analysis of the magnesium content was examined, to distinguish between calcitic and dolomitic marbles. Craig and Craig (1972) first suggested using isotopic patterns, plotted on a $\delta^{18}O$-$\delta^{13}C$ diagram, to identify quarry sources of five classical Greek and Roman marble artefacts. They collected and analyzed a total of 170 samples from ancient quarries on Naxos and Paros (the Aegean Sea), as well as Mount Hymettus and Mount Pentelikon (Greece); and found that the marbles fell into well-defined isotopic clusters. The great advantage was the small amount of material necessary for the analysis (about 20 mg). This research started to establish an isotopic database of ancient quarries in terms of the provenance determination of marble artefacts, and to assist in the correct association of broken marble fragments (e.g., Herz and Wenner 1978; Herz 1988). Additional improvements in today's large database are provided by a statistical evaluation of marble data (Leese 1988). Due to the frequent overlap of the measured isotopic values from different quarries, plus the possible variability within a marble block of any one quarry, by itself this method is not sufficient to distinguish between all marble sources (Wenner et al. 1988). Instead, the combination of C-O stable isotopic analysis with mineralogical-petrographic characteristics (especially optical microscopy and X-ray diffractometry) suffices for most of the major Mediterranean white marbles (e.g., van der Merwe et al. 1995; Lazzarini et al. 1999; Pensabene et al. 1999; Gorgoni et al. 2002; Tykot et al. 2002). Strontium isotopes have also been found to be very useful for provenance studies (e.g., Barbieri et al. 1999; Brilli et al. 2005); however, a sufficient database of marble values of the strontium isotopes has not yet been created. The initial research on the ratio of Pb, Sr and Rb isotopes were tested on selected Greek marbles (Perdikatsis et al. 2006). The results displayed a satisfying discrimination of the studied marbles, especially in combination with the mineralogical study and the analysis of trace elements. Despite these positive results, more additional data is necessary to accomplish a decisive investigation.

Geochemical analyses of major, minor, and trace elements of carbonates by various analytical techniques such as X-ray fluorescence methods (Cabral et al. 1992), using the inductively coupled plasma source: ICP-MS (Green et al. 2002) or ICP-AES (Jongste et al. 1992) and instrumental neutron activation analysis INAA (Oddone et al. 1999), have also been included in many provenance studies of marbles. Even if most of the methods of evaluation of trace elements require only a small specimen (up to 10 μg in the case of INAA), the comparison and interpretation of the analyses are more difficult than in the case of other geochemical methods, due to the variety of equipment, consistent sample preparation, the process of measurement, measurement conditions, standardization, demands of financial factors, etc. The main disadvantage and limitation of this approach is in the fact that many trace elements vary more within the same quarry than among different localities; hence only some of them are useful for the marble's discrimination (Mandi et al. 1995). However, a multivariate statistical treatment of the trace element data has given better results, especially when it was combined with analytical data from other methods such as stable isotope geochemistry (Matthews et al. 1995).

Electron paramagnetic resonance (EPR) (also presented as electron spin resonance spectroscopy) has also been used with great success in marble provenance investigations (Mandi et al. 1992) as well as in the identification of joining fragments of ancient marbles (Attanasio and Platania 2000). Initially, only manganese spectra were studied, and their EPR peaks (Mn^{2+} sextet) were compared by means of intensities (Baïetto et al. 1999). By measuring different spectral variables of the Mn^{2+} impurity (e.g., intensity of signal, integrated signal intensity, total spectral extension, splitting, and linewidth of the high field doublet) ubiquitously present in marbles, together with the addition of statistical evaluation, it has been possible today to establish a large database of EPR features (Attanasio et al. 2002). The technique is often used in combination with C-O stable isotopes and an elementary petrographic study (maximum grain size, colour, odour upon fracture) (Goette et al. 1999; Attanasio et al. 2000, 2005a, b).

Aside from the aforementioned petrographic and geochemical techniques, physical properties are also used for discovery of a marble's heritage. Conventional index parameters (measurement of open porosity, dry density, specific gravity), hydrophysical parameters (water absorption coefficients), and mechanical parameters (ultrasonic velocity) are often used for characterisation of a marble's quality. However, according to the findings of De Gennaro et al. (2003), mechanical strength tests (uniaxial compressive strength, point load strength, flexural strength) display satisfactory results in marbles differentiation.

9.3 A Methodological Approach Modified for Impure Crystalline Limestones: Examples from Czech Localities

9.3.1 Geological Setting of Czech Crystalline Limestones

The European countries including the Czech Republic show extensive marble deposits quarried for decorative purposes from early medieval times (Hanisch and Schmid 1901; Přikryl et al. 2001). Some examples of marble quarries studied from the Czech Republic are depicted on Fig. 9.1.

Numerous varieties of crystalline limestones (marbles *sensu stricto*) were involved with various tectonometamorphic and magmatic events in the area of the Bohemian Massif (Franke 1992; Chlupáč et al. 2002). Local carbonates form marble lenses and intercalations mainly in metamorphosed sedimentary rocks which exhibit high variability of metamorphic development. Contact metamorphism played a role mainly close to granitic plutons, e.g., in Silesicum (Fig. 9.1B) or in the Sedlčany-Krásná Hora Metamorphic 'Islet' (Fig. 9.1D). However, most of the studied carbonates were affected by regional metamorphism at variable intensity ranging from low-grade greenschist to amphibolite-facies conditions. This complex geological situation is reflected in the petrographic, geochemical, and physical variability of marble properties, namely in their diverse micro-fabric and the presence of non-carbonate phases.

9.3.2 Mineralogical-Petrographic Characteristics

Considering the micro-fabric, marbles exhibit layering parallel to the foliation (presence of shape preferred orientation (SPO) of carbonate grains) or quasiisotropic fabric as the result of the deformation and recrystallization history (Fig. 9.2).

Petrographic image analysis thus provides the required quantification of various fabric parameters of carbonate grains to allow a juxtaposition of petrographic

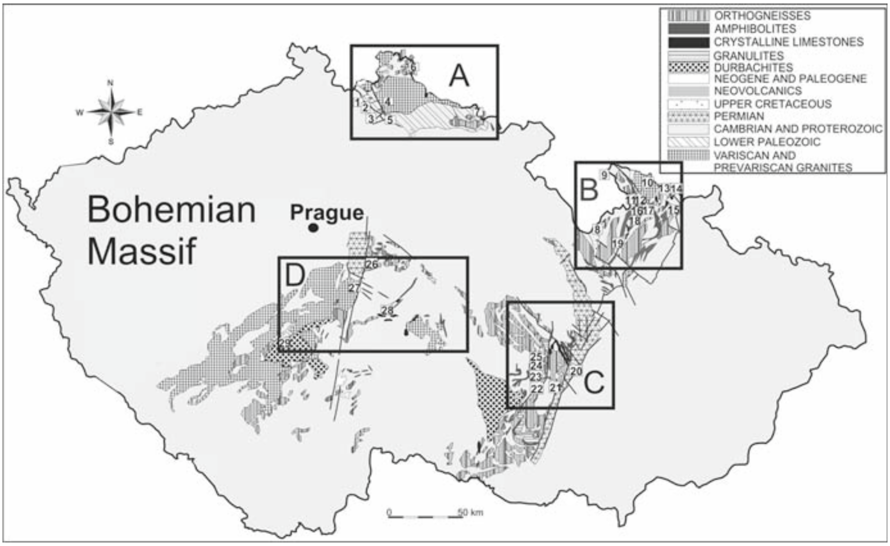

Fig. 9.1 A simplified geological map of the selected areas of the Bohemian Massif (Czech Republic) with sampled quarries. The legend of the geological map is valid only for areas **A**, **B, C** and **D**. **A** – Lugicum (Krkonoše-Jizera Terrane: 1 – Jitrava, 2 – Křižany, 3 – Pilínkov, 4 – Horní Hanychov, 5 – Rašovka, 6 – Raspenava, 7 – Strážné). **B** – Lugicum (Orlice-Sněžník Crystalline Unit: 8 – Velká Morava, 9 – Bílá Voda) and Silesicum (Mantle of the Žulová Granite Pluton: 10 – Staré Hradisko, 11 – Žulová, 12 – Vápenná, 13 – Strachovičky, 14 – Velké Kunětice, 15 – Supíkovice and Branná Group: 16 – Horní Lipová ,17 – Lipová-Na Pomezí, 18 – Branná, 19 – Bohdíkov). **C** – Moravicum (Olešnice Unit: 20 – Lysice, Devonian cover: 21 – Tišnov-Květnice, 22 – Tišnov-Dřínová and Svratka Crystalline Complex: 23 – Štěpánovice, 24 – Nedvědice, 25 – Ujčov). **D** – Boundary between Kutná Hora Crystalline Complex and Moldanubian Zone (26 – Sázava, 27 – Český Šternberk, 28 – Bohdaneč) and Sedlčany-Krásná Hora Metamorphic 'Islet' (29 – Skoupý)

characteristics with other properties. Although accessory minerals of most Mediterranean marbles are frequently too small and rare to allow stone types discrimination (Capedri and Venturelli 2004), impure marbles from Czech localities are characterized by the abundant presence of various non-carbonate minerals. The mineralogical composition of Czech marbles exhibits significant variability, they verge into calc-silicate rocks with a superiority of silicates in some cases (e.g., Český Šternberk marble, Figs. 9.3 and 9.4).

Optical microscopy as one of the traditional provenance techniques is still a very powerful tool for distinguishing these marble varieties. As a first stage, the method provides an important knowledge base with which to decide on the most suitable additional procedure. The identical sample (i.e., thin section) can be analyzed by different successive techniques (such as cathodoluminescence (CL) study, electron microanalytical techniques, etc.) which means an advantage especially in case of the artefacts research. An example of the impure marble from Český Šternberk demonstrates the useful combination of optical and electron microscopy with CL (Fig. 9.4). Cathodoluminescence observations detect discriminatory characteristics of carbonates as well as non-carbonate minerals, such as different micro-fabric, zoning and chemical composition, which can be latent in applying the optical microscopy.

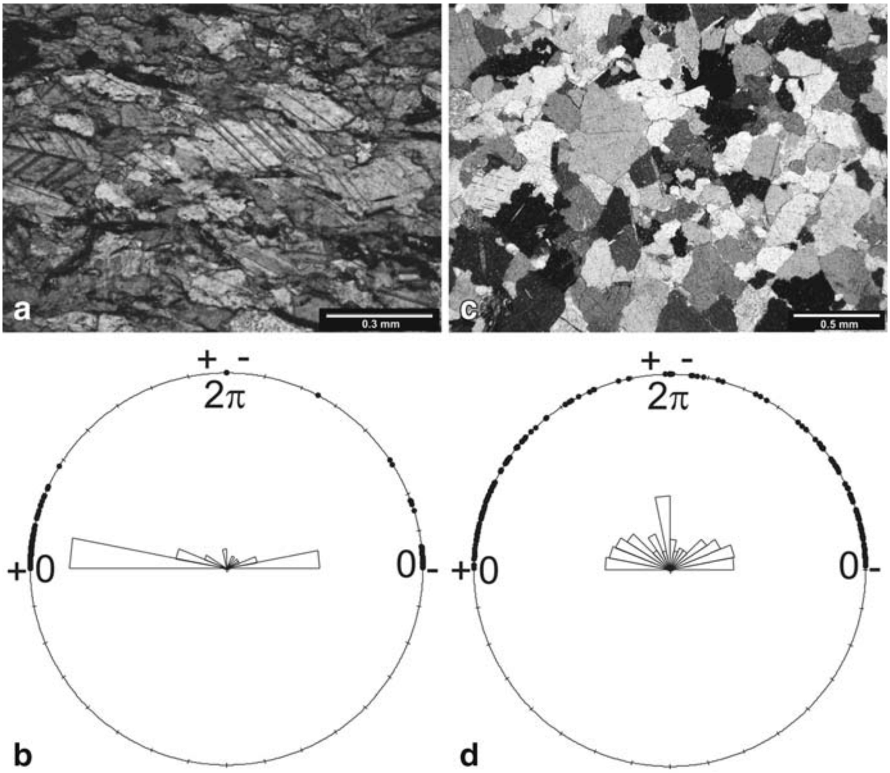

Fig. 9.2 Examples of the diverse micro-fabric of marbles from the Czech localities. **a** – Branná marble (Silesicum, NE Czech Republic, crossed nicols) exhibits layering parallel to the foliation with SPO and **c** – Bohdaneč marble (Boundary between Kutná Hora Crystalline Complex and Moldanubian Zone, central Bohemia, crossed nicols) displays quasiisotropic fabric with no SPO. **b** and **d** rose diagrams depict corresponding major axis slopes (in radians), each from 200 carbonate grains calculated from petrographic image analysis

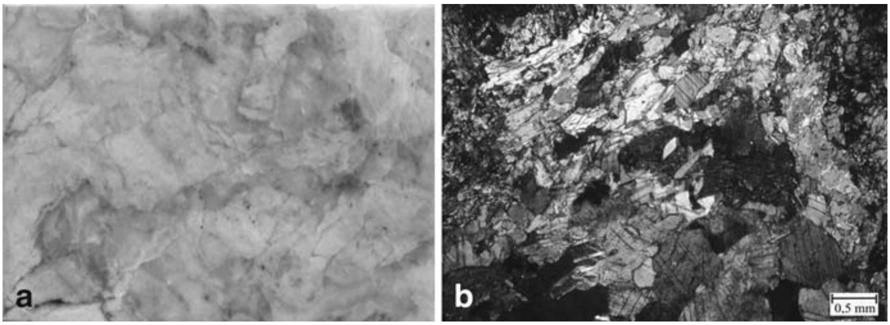

Fig. 9.3 Example of dolomitic marble rich in silicates from Český Šternberk (Boundary between Kutná Hora Crystalline Complex and Moldanubian Zone, central Bohemia). **a** – macroscopic character of the polished marble slab (real size 15 × 10 cm), **b** – microscopic image (crossed nicols) of the marble with predominant non-carbonate minerals (e.g., diopside, tremolite, phlogopite, muscovite, Mg-chlorite, quartz, feldspars, titanite)

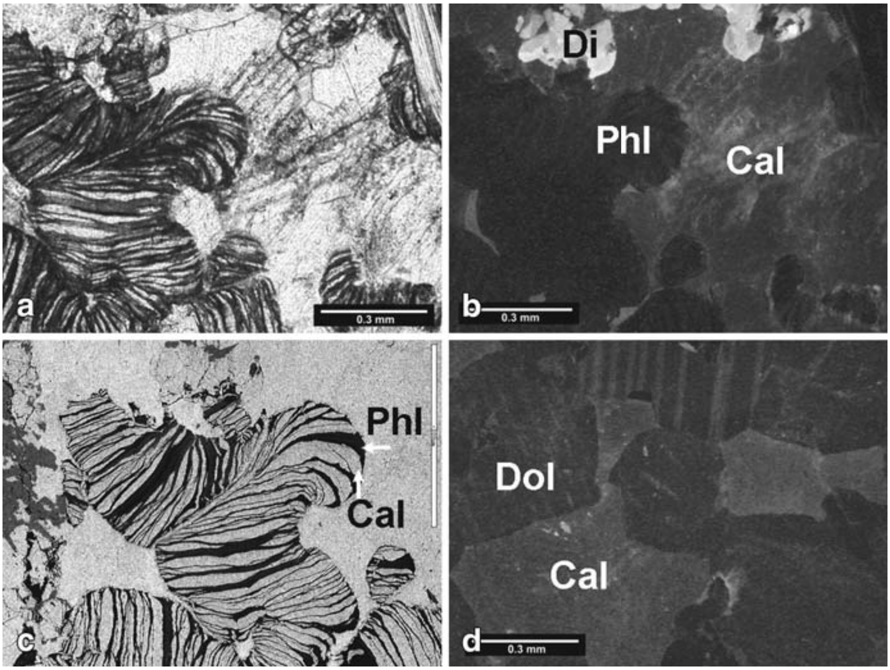

Fig. 9.4 Example of dolomitic marble with phlogopite (Phl) and diopside (Di) from Český Šternberk (Boundary between Kutná Hora Crystalline Complex and Moldanubian Zone, central Bohemia). Microscopic images describe different information that can be obtained by various techniques: **a** – optical microscopy, plain polarized light, **b** and **d** – cathodoluminescence (cold cathodoluminescence equipment), identification of non-carbonate minerals (Di, Phl) and clear differentiation calcite (Cal) from dolomite (Dol), **c** – scanning electron microscopy (SEM-EDAX photograph)

The traditional carbonate grain size evaluation was revealed as another discriminating parameter. Although fine-grained grey marbles exhibit very similar micro-fabric and grain size parameters, impure marble types rich in non-carbonate minerals show a wide range of average grain size. The mean grain size represented by the equivalent diameter (ED) is between 0.01 and 1.60 mm. The overview of mineralogical-petrographic characteristics of the major types of Czech crystalline limestones is displayed in Table 9.1.

9.3.3 Mineralogical-Geochemical and Physical Properties

Under the optical microscopy, the grey marbles often exhibit similar character and morphology of the carbonaceous matter. Raman microspectrometry represents a powerful additional technique when variously metamorphosed organic matter occurs. This method characterizes the structural state of various types of dispersed

Table 9.1 Overview of selected marbles from historical quarries, their mineralogical-petrographic characteristics with the equivalent diameter (ED) (average values of 200 grains of each thin section) and maximum grain size (MGS) of carbonate grains. Accessory phases: Ap: apatite; Chl: Mg-chlorite; CM: carbonaceous matter; Di: diopside; Ep: epidote; Fo: forsterite; Hem: haematite; Kfs: K-feldspar; Lim: limonite; Mg: magnetite; Ms: muscovite; Phl: phlogopite; Pl: plagioclase; Py: pyrite; Pyr: pyrrhotite; Qtz: quartz; Srp: serpentine minerals; Ti: titanite; Tlc: talc; Tr: tremolite; Wo: wollastonite; Zrn: zircon. SPO – shape preferred orientation (modified after Šťastná et al. 2009)

Group	Quarry	Geological unit	Mineral assemblage	ED [mm]	MGS [mm]	Micro-fabric
Grey calcitic marbles	Křižany	Krkonoše-Jizera Terrane (Lugicum)	Qtz+Ms(Phl)+Pl+CM±Kfs±Chl±Tr±Py±Pyr±Hem±Lim±(Ti±Rt±Zrn±Ap)	0.04	0.11	medium-strong SPO
	Rašovka			0.10	0.31	no-weak SPO
	Jitrava			0.01	0.05	no-weak SPO
	Pilínkov			0.17	0.56	weak-medium SPO
	Horní Hanychov			0.06	0.31	no-weak SPO
	Branná	Branná Group (Silesicum)		0.17	0.67	medium-strong SPO
	Bohdíkov			0.19	0.73	strong SPO
	Horní Lipová			0.51	1.69	medium-strong SPO
	Tišnov-Dřínová	Devonian cover, Olešnice Group (Svratka Dome, Moravicum)		0.05	0.27	medium SPO
	Tišnov-Květnice			0.04	0.14	medium SPO
	Lysice			0.48	1.70	medium SPO
	Sázava	Kutná Hora Crystalline Complex		0.16	0.66	weak-medium SPO

Table 9.1 (continued)

Group	Quarry	Geological unit	Mineral assemblage	ED [mm]	MGS [mm]	Micro-fabric
	Skoupý	Sedlčany-Krásná Hora Metamorphic 'Islet'		0.54	2.54	no SPO
White calcite-dolomitic marbles	Bílá Voda	Orlice-Sněžník Crystalline Unit, Krkonoše-Jizera Terrane, (Lugicum)	Qtz±Mus±Pl+Py±Lim±CM	0.18	0.38	no SPO
	Strážné			0.36	1.18	no SPO
	Raspenava		Tr±Srp±Fo±Phl±Di±Ms(Phl)±Qtz±Pl±Kfs+Chl±Py±Mg±Tlc±Zrn±Ap±Ti±CM	0.22	0.85	no-medium SPO
	Bohdaneč	Kutná Hora Crystalline Complex		0.39	3.17	no SPO
	Český Šternberk			0.51	2.70	no SPO
White calcitic marbles	Velká Morava	Orlice-Sněžník Crystalline Unit (Lugicum)	Mus+Phl+Tr±Di±Wo+Qtz±Pl±Kfs±Chl±Py+Ti±Rt±Zrn±Ap±Ep±CM	0.33	1.63	no SPO
	Nedvědice	Svratka Crystalline Complex		0.70	3.43	no SPO
	Ujčov			0.66	2.94	no-medium SPO
	Štěpánovice			0.10	0.44	weak-medium SPO
	Velké Kunětice	Mantle of Žulová Granite Pluton (Silesicum)		1.08	3.94	no SPO
	Strachovičky			0.41	1.06	no SPO
	Supíkovice			1.08	4.80	no SPO

Table 9.1 (continued)

Group	Quarry	Geological unit	Mineral assemblage	ED [mm]	MGS [mm]	Micro-fabric
	Staré Hradisko			1.56	6.39	no SPO
	Žulová			1.60	5.66	no SPO
	Vápenná			0.39	1.76	no SPO
	Lipová-Na Pomezí	Branná Group (Silesicum)		0.70	2.05	no SPO

carbonaceous matter by means of Raman spectra (e.g., Kříbek et al. 1994). The grey marbles, involved with amphibolite facies peak metamorphism (e.g., Lysice-Moravicum), display well-ordered carbonaceous matter to graphite *sensu stricto*. Very low regional metamorphosed marbles (greenschist peak metamorphism) (e.g., Jitrava, Křižany, Rašovka, Pilínkov-Krkonoše-Jizera Terrane; Tišnov-Moravicum) indicate poorly-ordered carbonaceous matter. Examples of Lysice and Rašovka marble, two variously metamorphosed crystalline limestones with similar character and morphology of metamorphosed organic material, demonstrate the usefulness of the technique for provenance studies (Fig. 9.5). The carbonaceous matter is accumulated in the carbonate rims in both cases. Raman spectrum which belongs to Lysice marble is typical of graphite (amphibolite-facies conditions); however, Rašovka marble metamorphosed in low-grade greenschist facies exhibits rather amorphous organic compounds as 'disordered' carbonaceous matter.

Impure marbles from Czech localities often include paramagnetic minerals with Fe-substitution such as pyrite, chlorite, phlogopite, diopside, or tremolite which slightly increase the bulk magnetic susceptibility. Ferrimagnetic minerals (magnetite and pyrrhotite) are present at three types of studied marbles (Raspenava-Krkonoše-Jizera Terrane, Horní Lipová-Silesicum, and Skoupý-Sedlčany-Krásná Hora Metamorphic 'Islet') which significantly increase the bulk magnetic susceptibility, up to 1700×10^{-6} SI (see Fig. 9.6). Regarding provenance studies, the major drawback consists in the random scattering of the magnetic minerals within the rock-sample, which can cause a range of magnetic data, even in a single marble type. An example is represented by Bohdaneč marble whose kappa values ranged from -0.73 to 178×10^{-6} SI.

9.4 Discussion

The fact that Czech marbles differ from most white marbles from 'classical' marble-producing regions, such as the Mediterranean area, also means that there are special requirements for the selection of provenancing techniques. Previously successfully used conventional analytical procedures such as X-ray powder diffractometry or stable isotope geochemistry may not provide the required discriminatory potential here due to significant variations in properties at individual localities (e.g., variable mineral content within one petrographic type of marble) and/or similar petrographic and geochemical parameters of marbles coming from different areas (Šťastná 2004, 2008). On the other hand, methods like e.g., Raman microspectrometry and bulk magnetic susceptibility, which were rarely examined for provenance studies, were shown to be very effective and discriminating for impure crystalline limestones (Šťastná et al. 2009). Research into metapelites, including metamorphosed organic matter by Raman microspectrometry, has been relatively widely employed in metamorphism studies (e.g., Jehlička and Bény 1992; Wopenka and Pasteris 1993; Yui et al. 1996). As the carbonaceous matter makes-up a common minor admixture included

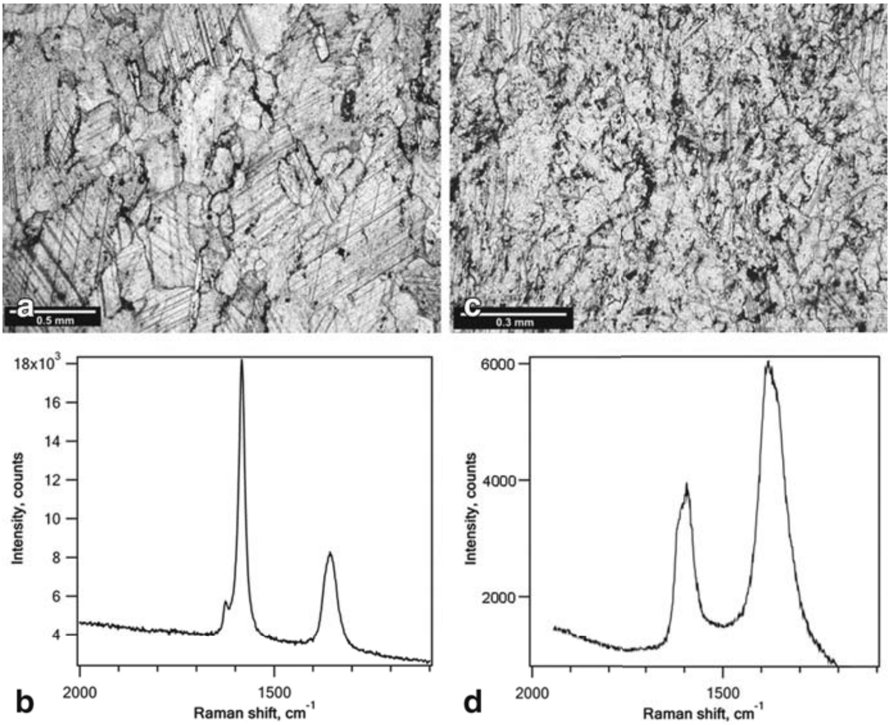

Fig. 9.5 Examples of the application of Raman microspectrometry on marbles from the Czech localities. **a** – Lysice marble (Moravicum, SE Czech Republic, plain polarized light) exhibits the carbonaceous matter which is accumulated in the carbonate rims and **c** – Rašovka marble (Krkonoše-Jizera Terrane, N Czech Republic, plain polarized light) displays similar character of carbonaceous matter. **b** and **d** Raman spectra depict corresponding structural state of the carbonaceous matter of marbles (**b**-graphite-Lysice; **d**-'disordered' carbonaceous matter-Rašovka) (modified after Jehlička et al. 2009)

in various marbles, the technique exhibits significant potential as a useful analytical method for fingerprinting graphitic marbles which have undergone diverse degrees of metamorphism (Šťastná et al. 2009; Jehlička et al. 2009). The advantage of this analysis consists in the development of portable Raman spectrometers, which at present have wide application in the artistic sector (Vandenabeele et al. 2007).

Magnetic susceptibility as one of the fingerprinting techniques widely used on various rock types such as granites (Williams-Thorpe and Thorpe 1983), trachytes (Capedri and Venturelli 2003), or laterites (Uchida et al. 1999); but marbles have been excluded, due to their predominantly diamagnetic character. Marbles from the Bohemian Massif include also magnetic minerals such as pyrrhotite and magnetite. Measurement of the bulk magnetic susceptibility thus represents an advisable contribution to the provenance studies for the determination of marbles with various magnetic properties (Šťastná and Přikryl 2009).

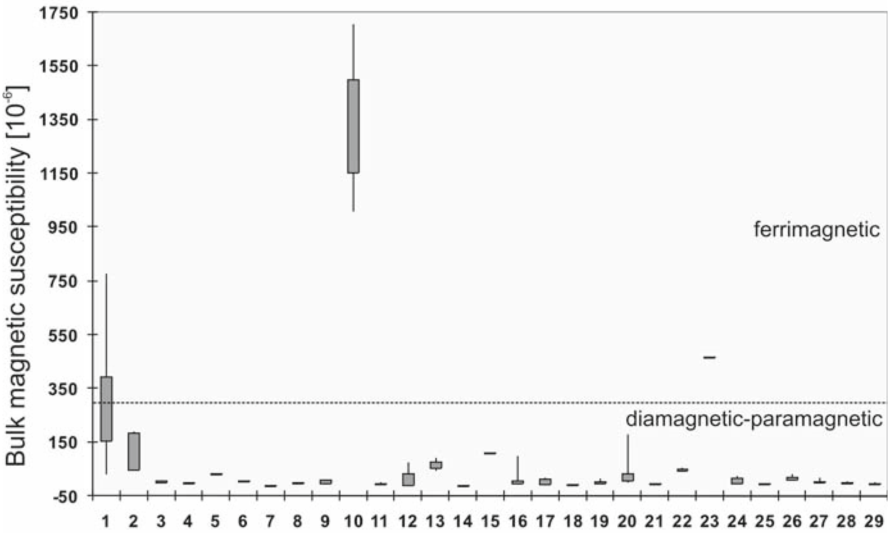

Fig. 9.6 The mean values of the bulk magnetic susceptibility of the selected marbles. The black-framed box bars show 25% (*bottom*) and 75% (*top*). The ends of the lower and upper whistlers represent the minimum and maximum values, respectively. 1 – Raspenava, 2 – Jitrava, 3 – Křižany, 4 – Horní Hanychov, 5 – Pilínkov, 6 – Rašovka, 7 – Strážné, 8 – Bílá Voda, 9 – Velká Morava, 10 – Horní Lipová, 11 – Lipová-Na Pomezí, 12 – Staré Hradisko, 13 – Žulová, 14 – Vápenná, 15 – Strachovičky, 16 – Velké Kunětice, 17 – Supíkovice, 18 – Bohdíkov, 19 – Branná, 20 – Bohdaneč, 21 – Sázava, 22 – Český Šternberk, 23 – Skoupý, 24 – Tišnov-Dřínová, 25 – Tišnov-Květnice, 26 – Štěpánovice, 27 – Nedvědice, 28 – Ujčov, 29 – Lysice. The dashed line (at 290×10^{-6} SI) distinguishes between diamagnetic-paramagnetic marbles and ferrimagnetic marbles

9.5 Conclusions

A large number of methodology studies dealing with natural stones (in particular, white marbles) of the Mediterranean area, where the provenance determination was examined in detail, have been published since the 1980s. Methodology of the provenance determination of marbles employs several mineralogical-petrographic, geochemical and physical techniques in general. From all of the methods referred to, it is evident that each analytical technique possesses certain advantages, but also some drawbacks; and thus no single method can provide reliable and accurate results in all cases, due to the frequent overlap of natural stone characteristics. The examination of various impure crystalline limestones coming from the European countries, including the Czech Republic, requires a different analytical approach that has not been fully applied in previous provenance studies. The highly variable character of local natural stones is mainly shown in their micro-fabric (type and degree of metamorphic involvement) and mineralogical composition (presence of non-carbonate phases). Applications of less common methods (e.g., Raman micro-spectrometry or physical properties like the magnetic susceptibility) can be more powerful in distinguishing marbles than some conventional methods (X-ray powder diffractometry or stable isotope geochemistry) in these cases. As it currently turns out, new approaches as well as further investigations of familiar analytical techniques (their confirmation and extension) are required for the correct fingerprinting of marbles from historic quarries and monuments. The combination of at least two methods providing completely unrelated information may represent the possible provenance key to the univocal determination of the source area of marbles used in historical monuments. The concurrent effort to establish a sufficient database of analytical data for complete natural stone collections is going on in most European countries. The application of the analytical techniques described, especially to various European marbles, has implications for the further development of knowledge in fingerprinting marbles as compared with the Mediterranean area.

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Chapter 10
In Situ Methods of Testing Stone Monuments and the Application of Nondestructive Physical Properties Testing in Masonry Diagnosis

Ákos Török

10.1 Introduction

Rapid in situ diagnosis of monuments is a key issue in the preservation of heritage sites. Stone masonry diagnosis is aimed to analyse the condition of a stone structure or building in order to understand the causes of deterioration and to find an adequate treatment and optimal conservation method or management plan for a heritage site or building. These measurements can provide valuable data for maintenance, restoration or they could form the base line of "preventive conservation". Due to the rapid development of measuring systems and the application of new methods and techniques from other fields (e.g., from the medical sciences) to masonry diagnosis, a wide range of techniques are available these days. The new methods such as portable spectroscopy units (Brunetti 2008), portable XRF (Thornbush and Viles 2006), combined XRD/XRF (Chiari 2008), X-ray tomography (Cnudde et al. 2009) or Light Detection And Ranging scanners (LiDAR, Meneely et al. 2008) and many other methods can revolutionize monument diagnosis in the future. Nevertheless, the widespread application of some of these new techniques is now hampered by their high costs and therefore in daily practice simpler and cheaper tools and methods are applied in masonry diagnosis. This chapter will describe both these new, expensive techniques and the older and generally cheaper equipments and methods of stone masonry diagnosis, focusing on testing physical parameters in particular.

The monitoring or detection of monumental stones and historic materials are becoming more and more of an important field for heritage preservation, which is indicated by the increasing number of congresses and workshops in this field (Tiano and Pardini 2008) and the increasing number of publications.

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The diagnostic tools can be used to measure the material properties of the masonry or the environment itself. The present review will focus on the testing of material properties and will not deal with environmental monitoring, such as temperature, humidity, wind etc. In other words it does not provide detailed information on the causes responsible for stone deterioration, but it gives details on the identification of the properties of stone masonry.

10.2 Tested Parameters, Objectives of In Situ Testing

Testing and diagnostic methods of stone monuments can be simply divided into two groups according to the type of property that is measured: (i) physical properties and (ii) chemical/mineralogical composition. The physical properties of the tested stones have a wide range: from visual appearance via surface properties to strength. The most important physical parameters and the typical methods of their in situ recording are given in Table 10.1.

Due to the recent development of portable devices the in situ testing of chemical and mineralogical composition can be performed in many ways. The analysed components can be broadly grouped into fields such as mineralogy, major- and trace elements and organic compounds. The typical components and equipments are listed in Table 10.2.

By using the above listed techniques the in situ testing can focus either on surface properties or bulk properties of monumental stones (Delgado Rodrigues 2008). Testing can be nondestructive (noninvasive) or moderately invasive with minor destruction of the surface. Coring or other larger samples can only be extracted from the monuments under special conditions (e.g., prior to stone replacement). The application of in situ tests is required for many reasons and the driving force is often the need for scientific investigations prior to restoration or long-term preservation of the site. It can be enforced by law or simply required by the architect, restorer or any other practitioner. There are three main possible objectives of the in situ tests:

- material identification;
- condition assessment;
- monitoring of changes (environment-related, treatment, etc.).

Table 10.1 Physical parameters and the most common in situ measuring tools

Physical property	Measuring tools/methods
Colour	Colour chart; Colorimeter, Spectrophotometer
Reflectance	Reflectometer
Temperature	Thermometers
Water content, moisture	Conductometer, moisture detector, thermographic imagery
Water absorption	Karsten pipe, Contact sponge method
Surface roughness	Micro-photogrametry
Surface morphology	Digital imaging, LiDAR
Strength	Micro-drilling resistance, Schmidt hammer, Duroscope
Apparent density	US pulse velocity measuring devices, US edge probe

Table 10.2 Chemical/mineralogical components and the most common in situ measuring tools

Chemical/mineralogical composition	Measuring tools/methods
Mineralogy	Portable XRD
Major elements	Portable XRF, UV-visual spectroscopy, Raman, Fluorescence
Trace elements	UV-visual spectroscopy, Raman spectroscopy
Organic compounds	FTIR-spectroscopy (Fourier Transformed Infrared Reflectance)

Material identification is often a key issue when proper stone types are needed for the restoration of a monument. Besides visual assessment, sampling and petrographic microscopy are used in provenance studies (see an overview in Přikryl 2007). Additionally, characterization of fabric very often helps in finding appropriate replacement stone (Přikryl 2006). Condition assessment is used to identify the preservation of the monumental stone and it generally documents the present condition of the material. Identification and scaling of decay and assessing degradation of the stone involved are essential goals of these tests. Finally, changes in properties and environmental conditions can also be addressed by using in situ masonry diagnostic techniques. A common case is monitoring the changing of stone properties due to various types of treatment (consolidation, anti/graffiti, etc.). For the evaluation of the efficacy, the same test procedures are preformed prior to and after treatment. These reference values are then compared with the measured values of the post treatment status. The environmental changes, such as climatic changes and more often air quality deterioration, are often manifested on stone surfaces. Typical features of environmental impacts that can easily be detected include colour change, formation of sulphated crust or accelerated soiling. Moisture or salt content are also partly affected by environmental changes and also related to the mineralogical composition of stone, render, mortar, paints or other compounds.

10.3 Physical Properties

10.3.1 Colour and Temperature

Colour and reflectance measurements are used for testing the visual colour changes related to soiling. The changes in colour can be given in numerical values by using the CIELAB colour chart and L^*, a^*, b^* colour scale (Billmeyer and Saltzman 1981). The darkness of the sample is given by the L^* coordinate (black to white), while its coloration is described by a^* (red to green) and b^* (yellow to blue) values. It has been demonstrated that air pollution cause severe darkening in stone surfaces as it is indicated by the L^* values (lightness) (Grossi et al. 2003, 2007; Brimblecombe and Grossi 2004). Colour measurements can also be applied to the detection of chromatic changes of fire damaged stones (Hajpál and Török 2004; Gomez-Heras et al. 2006; Dionísio 2007). The compatibility of replacement stones in terms of colour can be also controlled for by colour and reflectance measurements. The effect of cleaning and the treatment related colour differences can also be checked by using colour measurements (Grossi et al. 2007).

Temperature measurements of stone surfaces can be used to detect diurnal changes of ashlars and can also help in the identification of thermal dilatation and contraction related deterioration. The moisture content of the stone can also be indirectly related to surface temperatures, i.e., moist zones have lower temperatures than dry ones.

The visual assessment of stone types and doing micro-fabric analyses can also have a significant role in in situ diagnosis and also in the selection of appropriate stone types for replacement stones.

10.3.2 Water Content and Water Absorption

The water content of masonry materials is an important factor that influences the long-term behaviour of stones. Testing of water content by conductometry or thermographic imagery (Meinhardt-Degen et al. 2008) can help in the identification of endangered zones of scaling and decay. It can also be applied to the detection of capillary water uptake either from groundwater or from rain water. Wet zones can be delineated by using these techniques. When the test results of pre-treatment and water repellent treated surfaces are compared the efficacy of the treatment can be evaluated. The distribution of moisture in masonry structures influences the distribution of salts and salt migration pathways. Thus, moisture content analysis can provide valuable information on potential locations of salt subflorescence and efflorescence. Moisture and salt content can also be detected by using evanescent field dielectrometry (EFD) or unilateral nuclear magnetic resonance (uNMR) (Olmi et al. 2008).

Water absorption tests have been widely used in the detection of water penetration rate into the stone. Karsten-pipe tests aim to evaluate the in situ potential of consolidation treatment or water repellents (van Hees et al. 1995). They also provide information on the differences in water absorption of weathering crusts and host rock (Török 2002) and variously altered ashlars, as well as on the efficiency of consolidation (Bencharin et al. 2008). A contact sponge method has recently been developed to evaluate conservation interventions by measuring initial and post treatment water absorption (Pamplona et al. 2008). The methodology is based on a sponge that is pressed to the stone surface for 30 s to 5 min. From the mass difference of the initial wet sponge and the mass of the sponge after the test the water absorption can be calculated. Measurements of the contact angle of water drops or consolidants have been used for a long time especially for characterizing the hydrophilic or hydrophobic nature of protective coatings of stone surfaces. New computer aided techniques (CCD cameras and software) are available to detect the interaction of droplets and stone surfaces (Rius 2008).

10.3.3 Surface Morphology and Roughness

The latest techniques in surface roughness and surface irregularity measurements have a resolution of 0.1 mm. These include microphotogrammetry (Tiano et al. 2008), or fringe projection added photogrammetry (Boochs et al. 2008). These methods and new light detection and ranging (LiDAR) techniques allow the documentation of stone surfaces and surface morphology in 3D (Meneely et al. 2008). These methods provide visual impressions and often numerical values in the identification of deteriorating zones. Detecting short-term and long-term changes of stone masonry surfaces such as identification of areas with intense scaling or crumbling with these techniques give reliable results. Changes in soiling patterns (Thornbush and Viles 2007) and modification of stone surfaces by consolidation can also be documented by using photogrammetry. An object scanner provides an additional option for the detection of small scale changes (Smith et al. 2008). It is especially promising when images of initial stage and post treatment are available. A new method in the photographic detection of stone surfaces is Time-Lapse Macro-Imaging that has been used to detect surface loss in limestones over a period of a few months (Doehne and Pinchin 2008).

Another approach to surface roughness documentation has been implemented in rock mechanics. The ISRM (1981) standard method was mainly developed for testing discontinuity surfaces in rock masses, but its approach of using different techniques such as linear profiling (mm-scale ruler), compass or photogrammetry can also be used in monument surveys. According to the descriptive terms nine categories exist, but due to the larger scale of features, the adoption of these terms in the monument diagnosis is limited.

10.3.4 Surface Strength and Density

Strength and density of stone surfaces are very important parameters when the current state of the masonry material is assessed. The methods include micro-destructive ones such as micro-drilling resistance (5 mm diameter hole), or nondestructive ones, such as ultrasonic pulse velocity, Schmidt hammer (various types, see later) and Duroscope. The micro-drilling resistance test is based on a drilling device, with a drilling bit that penetrates into the stone with a constant rotation speed. The penetration force is measured with reference to the penetration depth and the drilling resistance value is defined along a depth profile (Tiano et al. 2000a). The equipment can be used to detect material strength with depth. The most important applications are analysing weathering profiles (Pamplona et al. 2007; Török et al. 2007a), or evaluation of the efficacy of consolidating treatments (Tiano et al. 2000b; Fratini et al. 2006). The drilling resistance can be correlated with the uniaxial compressive strength (UCS) of the stones (Exadaktylos et al. 2000; Pamplona et al. 2007). It is necessary to emphasise that due to the fact that it is a low invasive technique, which indeed generates a small drilling hole, it can be applied only for less visible parts of ashlar masonry; but it is surely not acceptable to use for the natural stone monuments of high artistic value or for sculptures.

A nondestructive surface strength tester is the Schmidt hammer. Initially it was developed for nondestructive testing of the strength of concrete but later it was applied to estimate rock strength (Irfan and Dearman 1978). The test mechanism of the Schmidt hammer is based on a spring-loaded mass that is released against a plunger when the hammer is pressed onto the stone surface. The plunger impacts the surface and the mass recoils, while the rebound value of the mass is measured either by a sliding pointer or a digital display. Several types of Schmidt hammer are available (e.g., Digi-Schmidt, N-34, L-9, PT-Schmidt) for testing stones and have different spring-force and thus impact load (Török 2008). The readings of the rebound values have no dimensions. These can only be converted to compressive strength or other parameters when parallel testing of stone surfaces and rock mechanical laboratory analyses are done. Formulas are available to recalculate Schmidt hammer rebound values to UCS for some lithotypes (Sabatakakis et al. 2008). With most Schmidt hammers it is possible to measure rebound values on vertical, oblique and horizontal stone surfaces, but the surface irregularities influence the accuracy of the tests.

The Duroscope is another surface strength tester. It is somewhat similar to a Shore test but it has a similar mechanism of operation to the Schmidt hammer. The Duroscope has a pointed plunger and smaller spring-loaded mass than the Schmidt hammer (Török 2008). The use of a Duroscope in the surface strength testing of rocks displaying various weathering features proved to be very efficient when relatively smooth surfaces are tested (Török 2003) but not suitable for testing deeply weathered irregular profiles.

Ultrasonic pulse velocities are often used for nondestructive in situ testing especially in terms of density and micro-crack identifications. In most US pulse testers a pulse emission source (transmitter) and a receiver are part of the equipment. According to the transducer geometries there exists a direct and an indirect method (Bellopede and Manfredotti 2006). In the first arrangement the longitudinal pulse travels in a perpendicular direction to the transducer's surface while in the latter one both heads are on the same side of the stone and the wave propagation is not perpendicular to the receiver. It has been documented that ultrasonic pulse velocity tests are excellent tools for diagnosing the decay of marble (Weiss et al. 2002), and the consolidation of various stones (e.g., sandstone, Myrin and Malaga 2008). A good correlation between ultrasonic pulse velocities and other physical parameters such as compressive strength and flexural strength were found (Bellopede and Manfredotti 2006). The ultrasonic pulse velocity shows a very similar trend to micro-drilling resistance (Török et al. 2007a) and can be used to estimate micro-drilling resistance, too (Bellopede and Manfredotti 2006).

A new technique, the ultrasonic edge probe, has recently been tested on masonry materials. The method uses one transmitting and two receiving transducers, which detect Rayleigh waves. The changes in wave velocities can be used as indicators of the deteriorating zones in stone and in brick (Skłodowski 2008).

10.4 In Situ Application of Physical Properties Testing; Selected Examples

To illustrate the application and the limitations of the techniques listed above, a few examples are given here. The temperature measurements provide valuable information on the surface temperatures of the stones and are especially important in the assessment of thermal dilatation/contraction related weathering of stones. The diurnal temperature changes and the differences in surface temperatures of the various lithotypes can be related to the exposure and can show significant daily changes (Fig. 10.1). A clear trend is observed throughout the day, with increasing surface temperatures till noon, and gradual decrease in the afternoon. Although sandstone is the darkest stone it had the lowest surface temperature.

Temperature differences are clearly observed on the ashlars consisting of the same lithologies having similar exposure to the sun. These differences can be attributed to variations in surface morphology and thus in weathering characteristics (Fig. 10.2). The trends of daily surface temperature changes from 9 a.m. to 4 p.m. are different at the northern wall (it is mostly in the shade) from the southern (sunny) wall. At the former one the daily maximum is in the afternoon; while on the sunny side the maximum temperatures were measured at noon. Weathering crusts have increased temperatures compared to scaling surfaces.

Water absorption tests with a Karsten pipe are very often used to test the ability of the stone to absorb not only water but also other consolidants. The performance of stone consolidation and the water repellence after treatment can be judged by using a Karsten pipe. This method can also be applied in assessing the differences in water absorption of weathered and unaltered stones. In most cases weathering

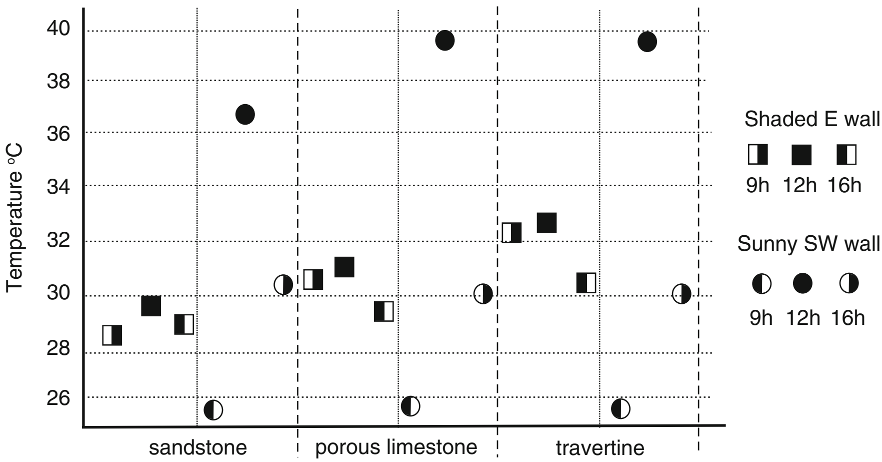

Fig. 10.1 Temperatures measured (mean values) on sunny exposed and shaded ashlars of various lithologies at 9.00, at 12.00 and at 16.00 o'clock, Buda Castle (Hungary) (modified from Schneider et al. 2008)

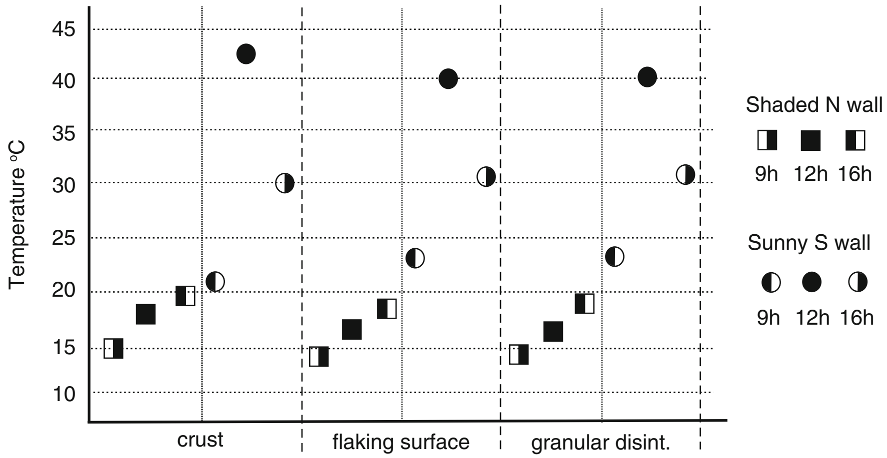

Fig. 10.2 Differences in temperatures measured on andesite tuff ashlars displaying various weathering forms, Visegrád Castle (Hungary). The temperatures were measured at 9.00, at 12.00 and at 16.00 o'clock and mean values are shown (data from Török et al. 2007b)

causes an increase in water absorption by opening new pores and cracks. Another trend was observed for weathering crusts. Karsten pipe tests clearly demonstrated that on porous limestones the formation of weathering crusts leads to the occlusion of pores and the reduction of water absorption, rather than an increase in water uptake (Fig. 10.3).

Simple dielectric in situ test equipment is used to analyse the relative moisture content of construction materials, such as stone. These portable devices often do not

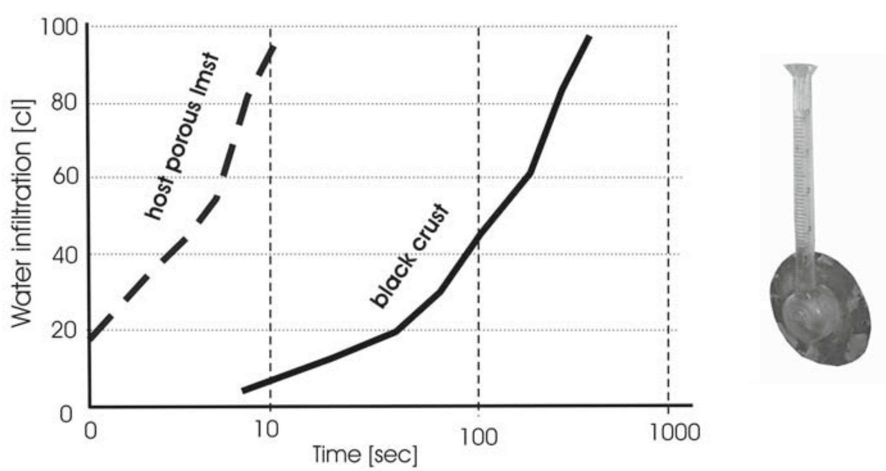

Fig. 10.3 Water absorption of weathering crust in comparison with host porous limestone (Karsten-pipe method, oolitic limestone, Budapest)

provide absolute values (percentage) of moisture content; but the obtained numerical values can be used in comparison with other measuring points and a profile of relative moisture content can be drawn. The example given here has been measured by a Gann-Hydromette Uni, a portable moisture content testing device. The surface morphology and micro-climate can significantly influence the measured values (Fig. 10.4). The base of the bluster is fairly saturated, but wind dries the middle part. The micro-morphology is also reflected in the distribution of moisture within this fairly porous stone.

Surface roughness measurements are often applied to detect weathering profiles or can be used in assessing conservation treatments. The test can reveal the changes in surface morphology by detecting the precipitated consolidants on the surface. Micro-drilling resistance also provides a good tool for detecting the zone of consolidation (Pamplona et al. 2008). It can also be applied in order to assess the depth of weathering profile or alternatively the formation of cemented surface zones. When various lithotypes are tested it is necessary to take into account the micro-fabric of

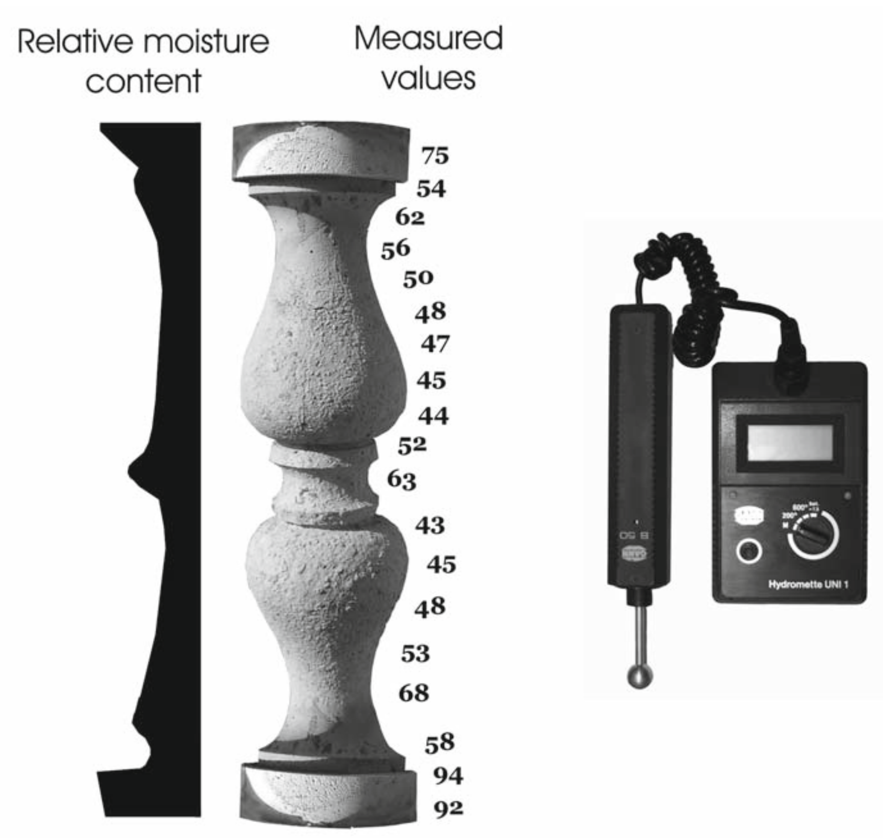

Fig. 10.4 Relative moisture content of a travertine baluster measured with a portable moisture tester (Basilica of Budapest)

the stone, since fabric irregularities can influence micro-drilling resistance. There is a clear difference between the micro-drilling resistance curve of sandstone and limestone. Nevertheless the surface alterations can be detected equally for both lithotypes. Although porous oolitic limestone exhibits drilling resistance less than sandstone, both the gypsum-rich weathering crust on limestone and the ferrous-crust on sandstone cause an equal increase in drilling resistance in the surface layer (Fig. 10.5).

The surface and sub-surface strength of stones are important indicators of decay. By using these techniques, features that are not visible to the naked eye can also be identified. The best utilisation of these in situ techniques occurs when large stone surfaces are tested and the rate of weathering of different parts of the stone structures are compared. Indeed they form an important part of decay mapping and diagnosis of masonry structures. With the Schmidt hammer and the Duroscope entire façades or individual stone structures can be diagnosed fairly rapidly. Several hundred in situ tests showed that there is a clear difference in rebound values of host limestone and various weathering forms (Fig. 10.6). With a Duroscope even very small differences in surface strength can be detected. The weathering crust and its cemented zone can have a different rebound value than the surface from which the crust has already been removed (Fig. 10.7a). This cementation and occlusion of pores, however, can lead to a reduced ability of water uptake which is also documented in

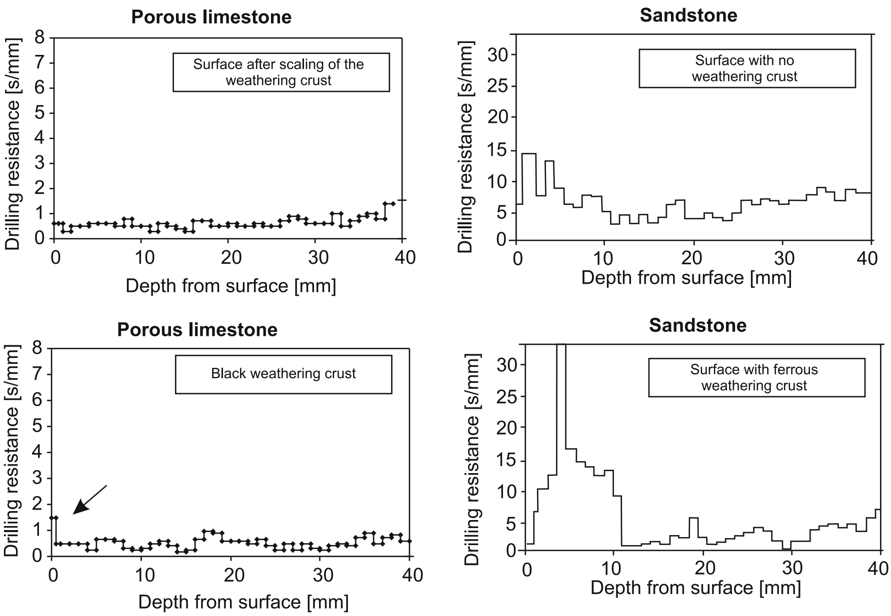

Fig. 10.5 Micro-drilling resistance of a gypsum-rich weathering crust of a porous limestone and of a ferrous-crust developed on sandstone. For reference two other curves are also given, where no weathering crust is observed (data from Török et al. 2007b; Schneider et al. 2008)

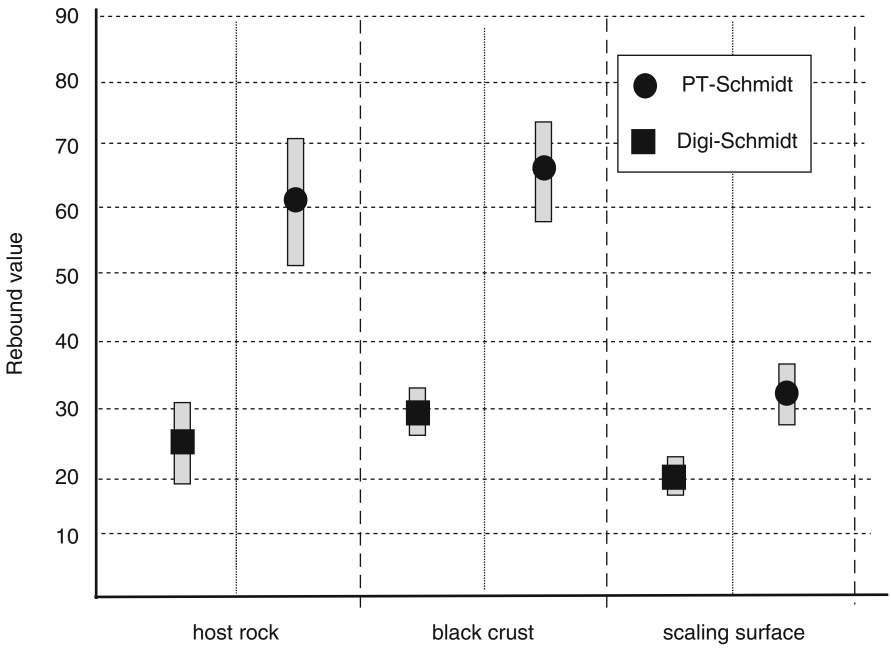

Fig. 10.6 Schmidt hammer rebound values measured by two different types of Schmidt hammer on the same porous limestone surfaces, which display various weathering forms (symbols represent mean values and grey bars are error bars) (Budapest)

terms of moisture content; this is to say that crusts have a lower moisture content than the host rock even on a very small scale (Fig. 10.7b).

10.5 Discussion

Although many of the techniques described above can be used very efficiently in stone masonry diagnosis, the application of individual techniques is often not appropriate for judging the present condition of the building stone. The reasons why one technique does not on its own provide representative results is related to the very inhomogeneous nature of the stone. Stone as a natural building material shows significant differences in fabric and even in mineralogy on a centimetre or even a micro-metre scale. Additionally, stone decay can be variable over the individual ashlar or slab (e.g., Smith 1996), or even over the entire structure (e.g., Fitzner et al. 2004), which means that by using only one technique the results can be misleading, since one parameter can be uniform, while another can show significant differences over an individual slab. A good example is porous limestone. It can show significant differences in terms of weathering features over a block scale at various locations in Oxford (Viles 1994), France (Beck et al. 2003; Rozenbaum et al. 2007), Malta (Cas-

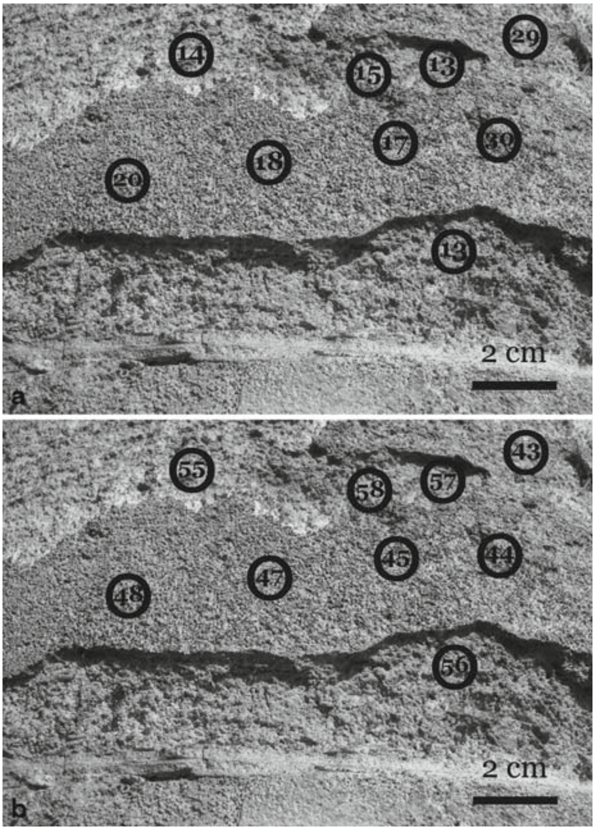

Fig. 10.7 Duroscope rebound values (**a**) and relative moisture content (**b**) of porous oolitic limestone with thin weathering crust (numbers refer to mean values). Moisture content was detected by portable moisture detector (see Fig. 10.4)

sar 2002) or Budapest (Török 2002). It has been documented that individual slabs can display multiple scales (Smith et al. 2003) or even granular disintegration (Török 2002). In terms of physical properties it leads to significant variations in Schmidt hammer rebound and Duroscope values (Török 2003). By using a Schmidt hammer and a Duroscope it is possible to detect smaller scale and also large-scale differences in strength. By using these techniques the strength is measured on a relatively small area (Duroscope 2 mm, Schmidt hammer 1 cm). To obtain reliable results that can provide a mean value of an entire slab or block, at least 10 measurements are necessary. The measuring points have to be distributed at roughly equal distances on each block. The difficulties in interpretation of the results come, as has been shown above, when the block displays various decay features or shows great variety in rebound values. The differences in rebound values can be attributed to various rates of decay (e.g., scaling crust or intact crust), or different rates of consolidation. Lithological differences can also cause a significant shift in rebound values, in drilling resistance and/or in other parameters. Examples include intraclasts in limestones, xenoliths in igneous rocks or larger quartz pebbles in sandstones. Fabric related anisotropy can also influence test results (Sabatakakis et al. 2008). Stratification, schistosity or other visual or non-visible anisotropic features can cause a significant scatter in the results of any in situ tests. Thus the interpretation of rebound values or other parameters needs special care in terms of data evaluation and statistical calculations. It has been documented previously that geostatistical techniques can be efficiently applied to weathering studies of building stones (McKinley et al. 2006). When in situ tests are considered as base lines for restoration works engineers and restorers are often faced with other limitations. When a building or a historic site needs structural engineering, reinforcement or reconstruction, numerical values are needed for calculations. The same applies when consolidation or other treatment is needed; the restorers need numerical values as to porosity, and absorption. Few in situ tests provide exact values of strength, permeability, porosity, etc. To overcome this problem, when it is allowed blocks are taken from the monument and analysed in the laboratory (mechanical and other parameters are then obtained), and analogues or numerical formulas are used for the calculation of values. There are significant drawbacks when analogues or formulas are used since only a limited amount of data sets are available for the various techniques and various stones. A few exceptions are microdrilling resistance analyses of selected lithologies (Pamplona et al. 2008), Schmidt hammer tests of granitic rocks (Aydin and Basu 2005), tuffs and a few other lithotypes (Sabatakakis et al. 2008) or ultrasonic pulse velocities of a few marbles (Weiss et al. 2002), limestones and sandstones (Bellopede and Manfredotti 2006). All these limitations clearly suggest a need for a large data base and numerical formulas for several lithologies to increase reliability of in situ material testing.

The in situ testing of monuments and monument diagnosis requires having permission and conforming with legal regulations. It is necessary to emphasize that there are different approaches to monument diagnosis within the EU and other countries worldwide. There are no international standards or rules (UNESCO, ICOMOS etc.) accepted worldwide that regulate the use of nondestructive tests or clearly set up legal limitations to the use of invasive techniques. It should also be kept in mind that the jurisdiction significantly differs from country to country and what might be legal in one country is illegal in other countries. Practitioners, scientists and authorities are not necessarily in agreement on the detail of monument preservation and the application of the necessary diagnostic tools. The interests of scientists and of the industrial lobby; i.e., the production of scientific results and the application of new and often costly interventions are not inevitably equal to a better understanding of the processes and approaches required for monument preservation. In several cases no intervention gives better results in the long term than intervention. Consequently, the selection of in situ testing methods and the interpretation of the in situ test results needs special care and very often brings legal and ethical issues to the surface.

10.6 Conclusions

There are several approaches to in situ diagnosis, which require various scales and detection time spans and the involvement of very simple or advanced techniques. The selection of a proper technique is limited by the accessibility of the monument, by the availability of techniques and also by the financial background. One technique is very often not appropriate for judging the present condition of the stone masonry structure, since stones are ab ovo non homogenous materials. Additionally, weathering or any conservation trial can exaggerate this heterogeneity by inducing further changes in chemical and mineralogical composition and physical properties. Even with stones where the fabric is considered fairly homogeneous (e.g., silica cemented sandstones), the measuring techniques can miss minor changes (e.g., differences in salt content), which can later lead to catastrophic decay at certain blocks or ashlars. Consequently, the application of multiple techniques increases the reliability of stone diagnosis and very likely reduces the chances of misdiagnosis of stone deterioration. The testing of the physical properties of monuments is very difficult in terms of obtaining numerical values for strength calculation, since most nondestructive tests provide relative values. Although some formulas and calculations are already available, additional research and new data sets are necessary to combine destructive laboratory test results (UCS, etc.) with in situ diagnostics.

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Part III
Binders, Concrete and Mixed Materials

Chapter 11
The Use of Lime Mortars in Restoration Work on Architectural Heritage

Ana Luque, Giuseppe Cultrone and Eduardo Sebastián

11.1 Introduction

Lime mortar is a mixture formed by kneading together aggregates, lime and water. It is one of the most frequently used materials in the history of building and was widespread even in ancient times with remains being found in houses in Delos and Thera (Gaspar Tébar 1996), and in buildings in Festos and Malia (Furlan and Bissegger 1975; Malinowski 1981).

Its use however has varied at different times in history, and it almost went out of use when Portland cement appeared in 1824, because cement offered certain advantages such as fast setting and high mechanical resistance (De Buergo Ballester and González Limón 1994; Radonjic et al. 2001).

In recent years lime mortar has staged something of a comeback, and is used especially in restoration work on historical buildings (Bromblet 1999). There are two main reasons for this. Firstly, its high chemical and physical compatibility with the materials normally used in these buildings (Iglesias Martínez 1996; Pérez Monserrat and Baltuille Martín 2001), and secondly its mechanical properties, which make it capable of resisting some degree of movement in the masonry. By contrast cement mortars, which in theory are stronger, are in fact less able to resist earthquakes (Hendry 2001). They are often incompatible with the materials used in historical buildings, and in some cases instead of repairing the damage to the building they have actually worsened it, causing decay that often proves irreversible (Arandigoyen and Alvarez 2007; Storemyr 2004). Another disadvantage of cement mortars is that salts from the alkalis normally contained in Portland cement have been shown to cause decay in the building stone (Hekal et al. 2002). The decline in the use of lime-based mortars was largely due to their slow carbonation which

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meant that they took longer to harden than cement mortars. Carbonation is a natural process that makes mortars harder and therefore more durable (Lanas and Álvarez Galindo 2003). This process depends on many factors including CO_2 concentration, temperature and relative humidity (Dehilly et al. 2002; Martínez Ramírez et al. 2003) and normally involves an increase in weight caused by the transformation of portlandite into calcite (Moorehead 1986, Dehilly et al. 2002). It has been observed that the total carbonation of mortar could take many years or even centuries (De La Torre 1995).

The study of lime mortars is now of great interest to restorers and conservation scientists involved in the safeguarding of our Architectural Heritage, however a better understanding of these materials is still required in order to promote their use.

Our objective in this work is to provide the restorer and researcher with a practical guide to important aspects of lime mortars that can be applied in their work on our Architectural Heritage.

11.2 Preparation of Lime Mortars

Although the process of making a lime mortar is apparently quite straightforward, research has shown that careful control in the selection of materials and in the manufacturing process does help to produce a high quality mortar. The choice of a particular aggregate or binder is therefore very important, as is the way the mixing process is carried out.

Nowadays there are a lot of regulations and standards that control the quality of the materials used in the kneading of lime mortars (UNE-EN, UNI-EN, ASTM, etc.). As far as the kneading process is concerned, however, although there are regulations, these tend to focus on the preparation of another kind of mortar, the cement mortar. Lime mortars and cement mortars have different properties which mean that these regulations cannot always be applied to the preparation of lime mortars (Cazalla 2002).

11.2.1 Selection of Materials

In ancient times, the choice of aggregate or binder was not subject to the same tight controls as today. This choice is however fundamental, as for example if a mortar is prepared with a lime that is not well fired or is partially hydrated, the result will be a poor quality mortar.

In the past the aggregate used by builders was generally taken from areas near the building site or very often from rivers. Today, however, there are specific rules as to its granulometry, the size of the grain, the porosity, surface, shape and the chemical and mineralogical composition. Of the aggregates currently available on the market, those of a siliceous composition are normally the most suitable. This

Table 11.1 Classification of limes according to UNE-EN 459-1/AC (2002) norms

	Firing temperature of raw material (ºC)	Clay content (%)
Air limes	800–900 Set in contact with air	≤5
Hydraulic limes	1050–1150 Set in contact with air or with water	5–22

type of aggregate was the one most commonly used in ancient times and shows great hardness and chemical resistance (De Buergo Ballester and Gonzalez Limón 1994), in addition to its good mechanical properties, durability and adherence.

As for the lime, this is a generic term used to describe all the physical forms in which calcium oxide (CaO), magnesium oxide (MgO), calcium hydroxide $Ca(OH)_2$ and magnesium hydroxide $Mg(OH)_2$ may appear. The UNE-EN 459-1/AC standard classifies limes on the basis of the environment in which they set and/or harden (they are also classified on the basis of their state in oxide or hydroxide form and their water content, Table 11.1) and on the basis of their chemical composition.

In general, and bearing in mind the use to which the mortars will be put, slaked lime of the air-slaked or fat lime varieties with a CaO content of over 90%, in either paste or powder form has been shown to be the best lime to use in the preparation of lime mortars (Elert et al. 2002 and references therein). There are also dolomitic limes in which the MgO content is over 10%. However this binder is much less frequently used (De La Torre et al. 1996). In our experience studying Muslim buildings (9th to 16th centuries) for example we have never come across it. The lime they used was known as “old” or “aged” lime putty. This type of lime was used after submerging it in water (on rafts) for long periods of time.

Nowadays the product most widely manufactured is slaked lime in dry powder form (hydrated in a stechiometric way), while lime putty which is often better quality is very hard to find. This creates a problem when it comes to selecting the best lime to use to make the lime mortar. It is therefore very important to find out how these limes are worked and how similar they are to the “old” limes and what advantages and disadvantages they offer compared to the “old” limes once in place on the building.

11.2.2 Kneading Process

According to Cazalla (2002); Martín Pérez (1990); and Hoffman and Vetter (1990), the best binder-aggregate mix is 1:3, and this is also the most widely used in mortars for restoration work (Malinowski 1981; Sbordini Mora 1981). In our experience, however, if lime putty is used, this ratio can be higher (1:4 or 1:5) without the mortar losing any of its technical quality.

Opinions are divided as to the best order in which to add the materials. On the basis of our experience and depending on the form (“putty” or “dry powder”) in which the lime appears, we recommend adding the materials in the order set out

Table 11.2 Changes in the sequence of materials we have to add during the kneading

	Lime putty	Dry powder lime
Sequence	lime + sand + water	lime + water + sand
Dosage	1+3 + 0.5 or 0.9	1+1 + 3

in Table 11.2. When working with limes in putty form, add the lime first, and then the aggregate and while these are being mixed together, gradually add the water in a very careful, controlled way. When working with limes in powder form, the lime must first be mixed with water and then kneaded, until a homogeneous paste with no lumps appears. Add the sand to this paste and continue kneading, so as to ensure that the final mortar paste is as evenly distributed and workable as possible (Ashurst 1990).

11.3 The Carbonation of Lime Mortars

11.3.1 Weight Increase Through Carbonation

The carbonation process that takes place in a mortar is caused by a reaction in which portlandite $Ca(OH)_2$ is transformed into calcite $CaCO_3$. This process is influenced by the diffusion of CO_2 through the pores of the mortar, by the dissolution of CO_2 and $Ca(OH)_2$ in the water that condenses in the pores and by the chemical equilibrium that is produced in this solution and the resulting precipitation of $CaCO_3$ (Van Balen and Van Gemert 1994).

Using X-Ray diffraction we can obtain valuable information about the degree of carbonation of a mortar, as we can measure the amount of calcite produced and then compare it to the amount of portlandite that remains after a certain period of time (R parameter defined by Cazalla et al. 2000). We do this by comparing the lines of maximum diffraction intensity for the calcite and the portlandite ($2\theta = 29.400$ and $2\theta = 34.033$, respectively) (Fig. 11.1). During the first few days of curing, we could clearly observe how the peak showing the maximum intensity for portlandite was higher than the peak for calcite, while after a certain period of curing the peak for calcite was higher than that for portlandite. This shows that the carbonation process continues over time and can be considered to have come to an end when the diffractograms no longer show diffraction lines for portlandite.

It is important to understand the carbonation process, as the material is modified not only from a mineralogical point of view but also in a textural and mechanical sense. To help us to understand this process better we can simulate it in the laboratory by subjecting the mortars to forced carbonation processes and then compare them with similar samples that have carbonated naturally.

We observed that lime mortars subjected to forced carbonation in a weather chamber with a temperature of 25ºC and a relative humidity of 50% registered a

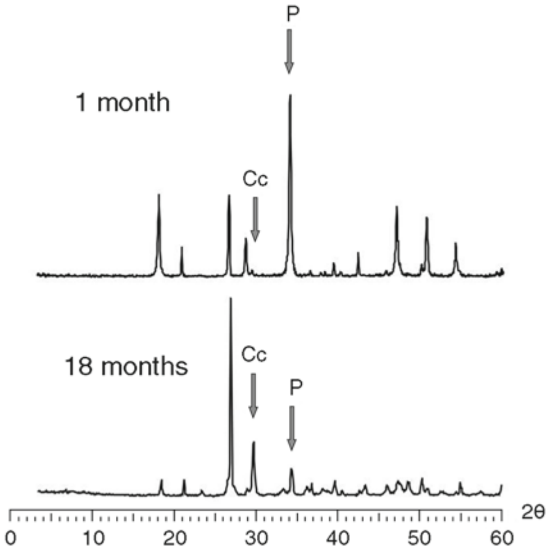

Fig. 11.1 XRD diagrams of a lime mortar after one month and after 18 months of carbonation. Legend: Cc = calcite; P = portlandite

weight increase of 6–7% after 30 days. We also studied the behaviour of mortars with certain additives to see if these would in any way enhance the carbonation process. Mortars to which additives had been added (we studied the behaviour of lime mortars without additives and others with pozzolana and/or an air-entraining agent) obtained lower values. It is important to note that, after just eight days all the mortars (with or without additives) had already reached their maximum weight increase, and after that showed only small oscillations (Fig. 11.2a).

In contrast, the weight increase of the mortars subjected to a natural process of carbonation was less than 0.5% after 20 days and after four months the figure was still less than 2%. If the weight of the mortar were to continue increasing at the rate recorded during the first days of natural carbonation, it would take one year to obtain the same results as those obtained with the samples carbonated in the climatic chamber (Fig. 11.2b). Nevertheless, the rate of weight increase slowed down over time and entered an asymptotic curve when the weight increase was less than 3%, i.e., less than half the weight increase of the mortars subject to forced carbonation. After 6 months, the weight of the mortars was still rising, albeit very slowly.

Notice that all samples (forced and naturally carbonated) start to carbonate during the drying phase. The weight difference shown by these two groups of mortars after just 2 days of carbonation suggests that very little calcite would have been generated before the beginning of this test. Taking into account that temperature and relative humidity were the same for both forced and naturally carbonated samples, the CO_2 concentration during the carbonation process appears to be a decisive parameter in lime mortar carbonation kinetics. The higher the CO_2 concentration,

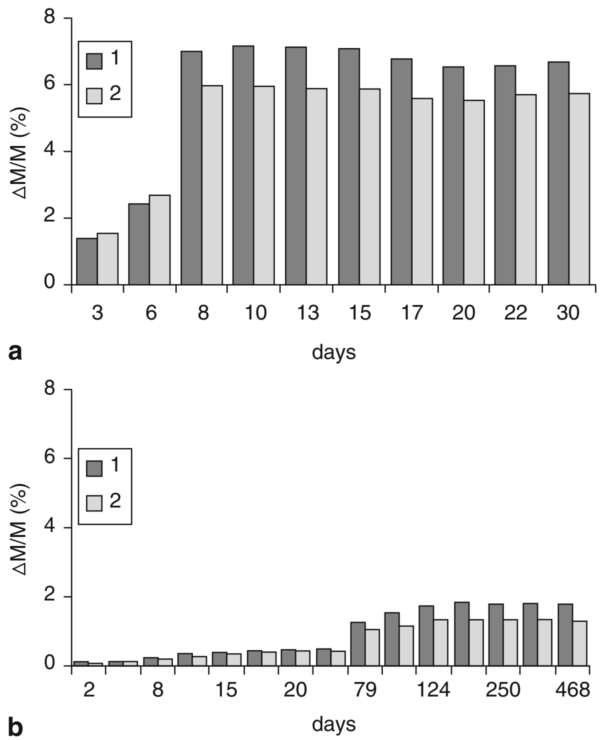

Fig. 11.2 Weight gain (in %) during forced **a** and natural carbonation **b**. 1 represents a mortar without additives, while 2 is a mortar with additive

the deeper the excess CO_2 can penetrate into the mortar block, thus producing a thicker carbonated area (leading to faster carbonation). At atmospheric CO_2 concentration, any CO_2 molecule entering the mortar pore system could rapidly react with $Ca(OH)_2$. Thus all CO_2 molecules will be "trapped" near the surface of the mortar, before the reaction front progresses to the sample core. As long as there is unreacted $Ca(OH)_2$ on the surface layer, the carbonation front will not progress towards the core of the mortar.

The reaction rate is independent of CO_2 concentration. The rate depends on the reactivity of the lime (i.e., surface area) and the water content (Van Balen and Van Gemert 1994). However, even if we consider a constant reaction rate, the higher the CO_2 concentration, the faster, the more thorough the carbonation process is.

Bearing in mind the molecular weight of calcite (100.09 g) and portlandite (74.09 g) and the densities of portlandite (2.23 g cm^{-3}) and α-quartz (2.53 g cm^{-3}), and considering that in these mortars three parts are occupied by the aggregate (α-quartz) and one by the lime, a weight increase of 7.91% could be expected if the portlandite was completely transformed into calcite. The 6% result obtained in forced carbonated mortars corresponds, therefore, to 75.85% carbonation of the initial mass of the lime. On the other hand, the 1.5% weight increase in naturally carbonated mortars indicates only 20.23% carbonation.

11.3.2 Calcium Carbonate Formation Through Carbonation

Figure 11.3 shows the graph of XRD analysis with regard to calcite concentrations in the mortars versus the time of carbonation for samples subjected to forced carbonation. There is a clear link with the results obtained by weight increase (cf. Fig. 11.2a), and mortars without additives reach the highest degree of carbonation. After 48 h more than 50% of the portlandite had turned into calcite. After 6 days the percentage of calcite was nearly 65% and after 8 days it was over 90%. This shows that after 8 days in a CO_2-saturated atmosphere almost all the mortar had carbonated, as weight increase data suggested. It is also clear that a 100% $CaCO_3$ value was not reached. The complete transformation of $Ca(OH)_2$ into $CaCO_3$ is difficult to achieve. This may be due to the heat that is produced during the transformation of portlandite into calcite, which in turn causes the capillary water inside the mortars to evaporate, especially when high CO_2 concentrations are present (Moorehead 1986). Van Balen (2005), however, demonstrated that the carbonation reaction of lime does not depend on the CO_2 concentration and that in fact the controlling factors are the presence of water and the specific surface of lime. This hypothesis may explain why the reaction in forced carbonated samples ended after only 8 days, while in naturally carbonated mortars the process can last for years.

A second factor that can impede or at least reduce carbonation is the environmental temperature. Dehilly et al. (2002) observed the complete carbonation of portlandite, probably because of the lower temperatures they used in their investigation. It is a well known fact that the solubility of CO_2 decreases as temperature increases (Moorehead 1986). Another cause may be the reduction in porosity during carbonation as a result of calcite crystallization, which reduces the space for gas molecules to migrate towards the calcium hydroxide crystals located inside the mortar (Stamatakis et al. 2001).

Therefore, the carbonation of mortar subjected to forced carbonation can start during the earlier drying phase, but contact with a CO_2-rich atmosphere (in the presence of water) is what accelerates the process. In fact, a comparison with the limited weight increase of samples subject to natural carbonation confirms this assertion.

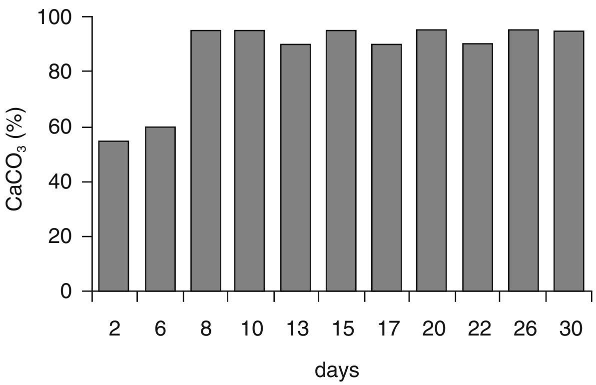

Fig. 11.3 Percentage of newly-formed $CaCO_3$ in mortars during forced carbonation

11.4 Fabric and Physical Properties of Lime Mortars

11.4.1 Crystals Morphology and Fabric

Scanning Electron Microscopy allows us to study the microfabric of mortars, the shape and size of the pores and/or fissures and the degree of adherence between binder and aggregate.

Lime carbonation determines changes in the morphology of the crystals. At the beginning of the carbonation process a large number of hexagonal, plate-like crystals of portlandite are visible (Fig. 11.4a). In some cases they are isolated, and in others they are heaped on top of each other. The size of these crystals can range from 200 nm to 1 µm. During the carbonation process, portlandite platelets disappear and are replaced by calcite crystals of irregular morphology (Fig. 11.4b). Finally, when the carbonation is almost complete, the mortar structure is covered by 1 µm wide scalenohedral calcite crystals with a few remaining portlandite platelets scattered amongst them (Fig. 11.4c).

As regards fabric, mortars can show fissures which cross the binder or move around the aggregate particles. These develop during mortar setting. Small pores can also be seen in the matrix (Fig. 11.5a). Additives can modify the fabric, especially if air-entraining agents are used. In this latter case, large, rounded pores are visible and impede the development of retraction fissures (Fig. 11.5b).

11.4.2 Porosity and Pore Range Distribution

The fact that the porous system of a mortar has changed is not a conclusive result when it comes to assessing the progress of the carbonation process. The only thing it shows us is that the mineralogical changes somehow produce changes in the textural properties of the mortar. In this case, a fall in the open porosity indicates that somehow the pores are closing. This is not surprising if we bear in mind that the volume of the calcite is higher than the volume of the portlandite. This increment corresponds to 11.8% (Lawrence 2005).

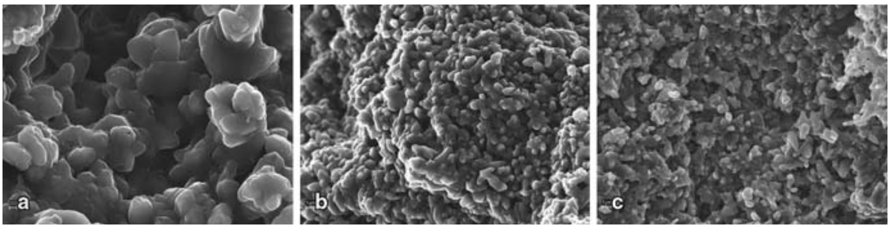

Fig. 11.4 SEM secondary images of mortar at different stages of carbonation: **a** at the beginning of the process; **b** during carbonation; **c** when carbonation is almost complete

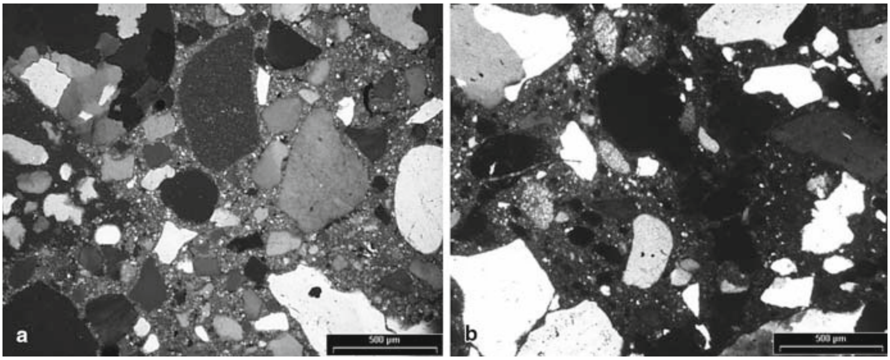

Fig. 11.5 Optical microscope photographs of a lime mortar without additives **(a)** and with air-entraining agent **(b)**. In the latter, round-shaped pores can be recognized

In general, a lime mortar with just a few days curing shows porosity levels of around 30–35%, while a mortar that has been curing for over a year shows falls in porosity to levels of around 25–28% (Cazalla 2002).

11.4.3 Elastic Parameters

The most interesting result shown by ultrasonic wave propagation is that after carbonation the fabric has been altered. This is logical because a fall in porosity leads to an increase in the homogeneity of the sample. We also found that average velocities in lime mortar specimens increased as time went by as a result of the carbonation process, from values of around 1800 m s^{-1} in the first few days of curing to values of around 2000 m s^{-1} after the first year (Cazalla 2002). The use of additives also affected the velocity of propagation of the ultrasound waves. The use of pozzolana, for example, increases the ultrasound velocity of mortars (changing them into hydraulic mortars), whereas the air-entraining agent causes the velocity to fall, due to the development of air bubbles.

11.5 Conclusions

We can control and complete the process of mortar carbonation using different techniques. Our results show that carbonation is progressive and occurs from the outside in, gradually over time.

When it comes to selecting a high quality lime, we must take into account the raw material and the manufacturing process which must be carried out extremely carefully. This process must include the correct firing, slaking, storage and handling of the product. After the slaking process, the lime must not come into contact with the atmosphere as this would cause it to carbonate.

Although previous studies indicate that mortars made with lime putty show higher levels of carbonation, our research shows that mortars made with lime powder can also reach comparable and even higher carbonation levels than those made with traditional lime putties. This may be due both to the quality of the raw material and to the carefully controlled manufacturing process through which mortars made with lime powder must pass.

The velocity of carbonation is a key parameter in any evaluation of the quality of a lime mortar. We have verified that once carbonate formation has reached high levels (i.e., 90%) under forced carbonation, the process slows down sharply. This may well be due to the great heat generated during the portlandite to calcite reaction, which causes capillary water to evaporate, and/or a high ambient temperature, which can reduce the solubility of the CO_2, and/or the pore size reduction caused by calcite crystallization.

Under natural environmental conditions carbonation is a lot slower, and does not reach the same volume as that achieved by forced carbonation. We have demonstrated the importance of CO_2 concentration in the portlandite-to-calcite velocity reaction under certain levels of relative humidity and temperature. The reaction rate mostly depends on the reactivity of the lime and water content.

The addition of air-entraining agents to the mortars helps to eliminate or at least to reduce significantly the retraction fissures that develop in other types of mortars. This additive does not increase the carbonation rate of lime mortars because although round pores develop, there is a low interconnection between the pores.

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Chapter 12
The Basilica of Maxentius and Its Construction Materials

Carlo Giavarini

12.1 The Basilica of Maxentius

It is well known that Roman basilicas served various public and administrative functions. The construction of the Basilica Nova, now known as the Basilica of Maxentius, was emblematic within the building programme of the emperor Maxentius (306–312 A.C.). Typologically, the building exploited several characteristics of Roman architecture (bath buildings, basilica halls, etc.), reinterpreting and combining them in a successful and original structural whole. The enormous potential offered by the extreme sophistication of Roman imperial building techniques was exploited to create the largest building covered with a system of vaults in the entire empire. The dimensions of the Basilica were 90 × 65 m (about 6,000 m^2), with the central nave alone occupying 83 × 25 m.

It was an innovative project, without immediate precedents, structurally based on the potential offered by that extraordinary Roman invention which was the use of concrete in vaulting. The problems linked to size and the speed with which the Basilica of Maxentius was erected had probably already emerged during construction. We can assume that not long after completion it suffered damage and natural disasters (earthquakes, poor maintenance and the removal of its precious marbles), with the result that more than half of the building collapsed. However, what remains (less than a third) is still astounding for its size and impressive boldness (Fig. 12.1).

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Fig. 12.1 The Basilica of Maxentius seen from the Palatine

12.2 The Studies and Research on the Basilica

Despite its importance, the Basilica of Maxentius had long been one of the least well-known monuments from late antiquity and for many years its true identity remained unknown.

During the important work undertaken by the *Soprintendenza Archeologica di Roma* to preserve the building on the occasion of the Jubilee, a new programme of studies and research began (Giavarini 2005). Among them a detailed structural study carried out by CISTeC has brought to light the minimal safety margins present in the Basilica of Maxentius in its current conditions, especially in the event of earthquakes (not frequent, but possible in the Rome area).

The investigations of the subsoil and foundations were equally important and made it possible to identify the causes of the deformations that have occurred in the past (Giavarini et al. 2002). The simultaneous execution of a detailed archaeological investigation permitted us to identify the procedures used for planning and construction. A detailed virtual reconstruction of the original Basilica was made (Fig. 12.2), with the identification of the static characteristics and structural limitations which had led to collapse.

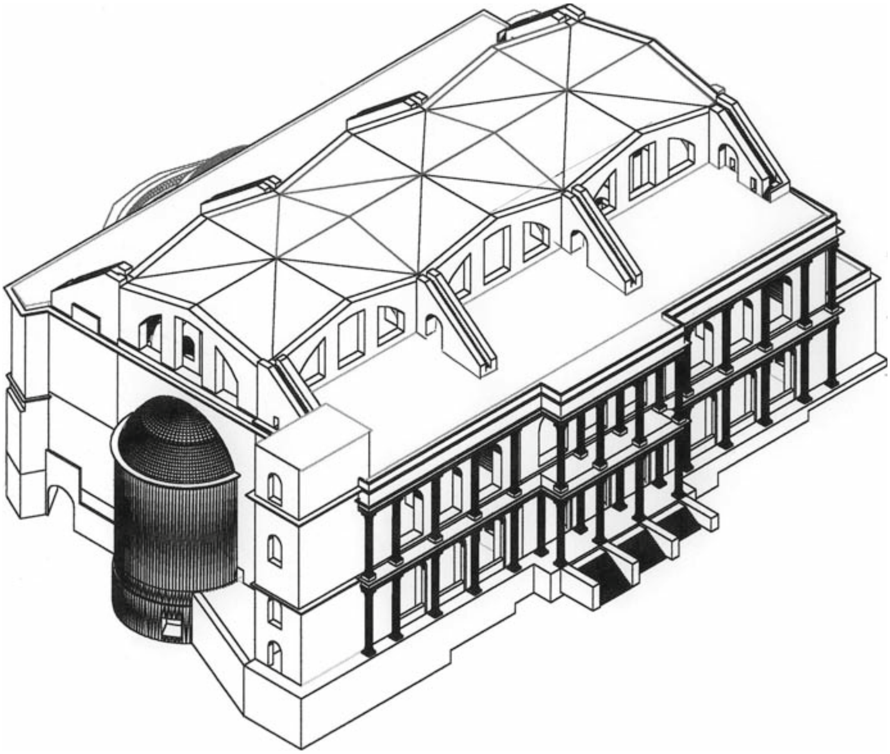

Fig. 12.2 Basilica of Maxentius. Rendering of the constructed exterior (by C.M. Amici)

12.3 The Importance of the Construction Materials and of Their Production

The astounding speed with which enormous buildings like the Basilica of Maxentius were completed must also have depended on the availability of materials and their industrial production on an immense scale. The importance of a regular supply of materials to any building project cannot be overestimated, especially when the construction schedule is tight and the building is being erected quickly. As for other comparable buildings, the basic materials for the large-scale construction project ordered by Maxentius were: lime and pozzolana to prepare the mortars, bricks, tufa, stone for the walls, metal, marble and anything necessary for the decorations (Vitruvius, Adam 1988). This without taking into account the other materials required during the various phases of construction, above all timber for scaffolding and the formwork.

The Romans understood their building materials well and knew how to produce them in industrial quantities whilst maintaining a constant level of quality. Many of the Roman buildings which collapsed did so because they were not looked after during the centuries subsequent to the fall of the Roman Empire or because pieces

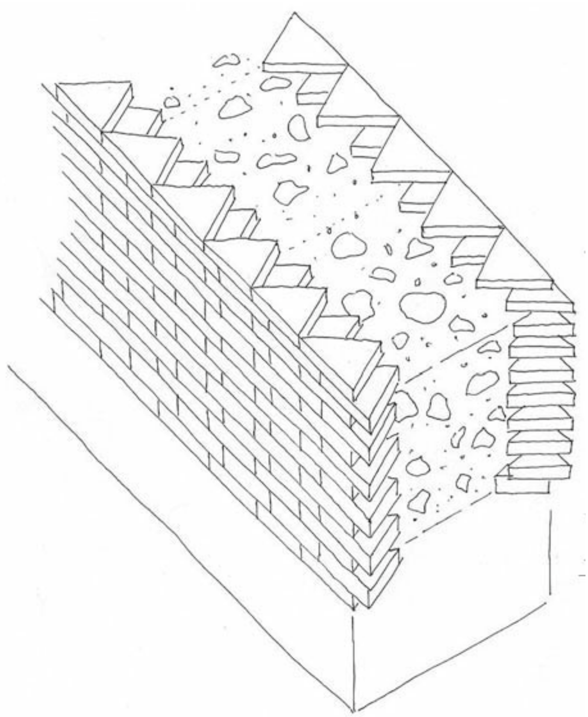

Fig. 12.3 Wall constructed with two facing walls in *opus latericium* and a concrete filling composed of lime, pozzolana and rough aggregate

were removed for reuse in medieval buildings. In most cases they did not collapse due just to construction defects or poor materials.

The imposing walls we see in Rome and many other Roman towns are often constructed in *opus latericium*, i.e., two facing walls (one on each side of the wall) between which is concrete composed of lime, pozzolana, and various types of aggregate (Fig. 12.3). In practice, the brickwork serves, especially in the thickest walls, only as facing.

12.4 The Use of Bricks in the Basilica

Buildings made entirely of brick were fairly rare in the Roman world before the 4th century. Though bricks did not play a primary structural role, they were an essential part of Roman architecture and were widely used to build the Basilica of Maxentius; we shall examine them in more detail.

12.4.1 Brick Production by the Romans

As said earlier, the first rule adopted by the Romans to make their buildings solid and long-lasting was to choose and prepare carefully the materials they intended to use. So although production techniques for bricks had remained unchanged for the previous 2,000 years, particular attention was paid to the choice and treatment of the clays, their mixing, drying and then their firing; all of this can be seen in the second book of Vitruvius' fundamental work *De Architectura*.

Even today we can but marvel at the fact that the Romans were able to produce such enormous quantities of bricks, such as bipedales (c. 60 × 60 cm), uniformly fired, with neither undulations nor cracks.

The clays were quarried and carefully aged before being mixed with water; when required, other products were added to correct the mixture. The Romans were well aware that the plasticity and workability of the clay improved after it had been aged while still moist (Vitruvius). After it had been well kneaded, the clay was pressed into appropriate wooden moulds, depending on the type of bricks that were needed.

It was considered preferable to make the bricks in autumn or winter, so that they would have time to dry out evenly (in a covered area) and the summer sun could complete the work. In this way, cracking was avoided, as was the risk of the surface drying too quickly, leaving the interior still moist.

Once they had reached the right degree of dryness, the bricks were piled in the kiln and fired with a wood fire which reached a temperature of 700–900°C (hotter fires were obtained when coal or charcoal were used).

During the firing process, the clay loses the moisture and undergoes dehydroxylation and structural changes, as amorphous silica and alumina are formed. At about 700°C, a small proportion of the silica melts due to the inevitable presence of modifiers of the chemical structure. At 900°C and above, aluminium silicates begin to form (Mariani 1974). The presence of these various phases is an indicator of the temperatures reached during firing.

As confirmation of the extraordinary planning capabilities of the imperial period, the shapes used in brick production were standardized from as early on as the 1st century A.D. The most common shape was a square, with sides measuring from 2/3 of a foot to 2 feet or 1.5 feet (bessale, bipedale, and sesquipedale respectively). In general their thickness varied from 2.5 to 6 cm (Giuliani 1998).

The industrial production of only a few types of brick avoided the use of many small separate moulds. The size measuring 45 × 45 cm was the most widespread since this was used to make the fractional triangular elements (*laterculi, semilateres*) used for the curtain wall (Fig. 12.4). The cut was probably made with a mason's hammer. This practice is confirmed by the discovery of sesquipedales with grooves or furrows scratched on them for subsequent cutting (Giuliani 1998). The Romans were thus able to obtain two triangular pieces from each bessale and up to 16 from each sesquipedale. As mentioned above, this practice was probably dictated by practical and industrial calculations made after comparing the times needed for production, handling, drying and firing, plus transportation, and storage. Furthermore, when a piece with pointed corners (such as a triangle) was fired, it was more susceptible to deformation. Nor should we overlook the fact that the cut (more porous) surface was placed so that it came into contact with the mortar, thus furnishing a stronger bond.

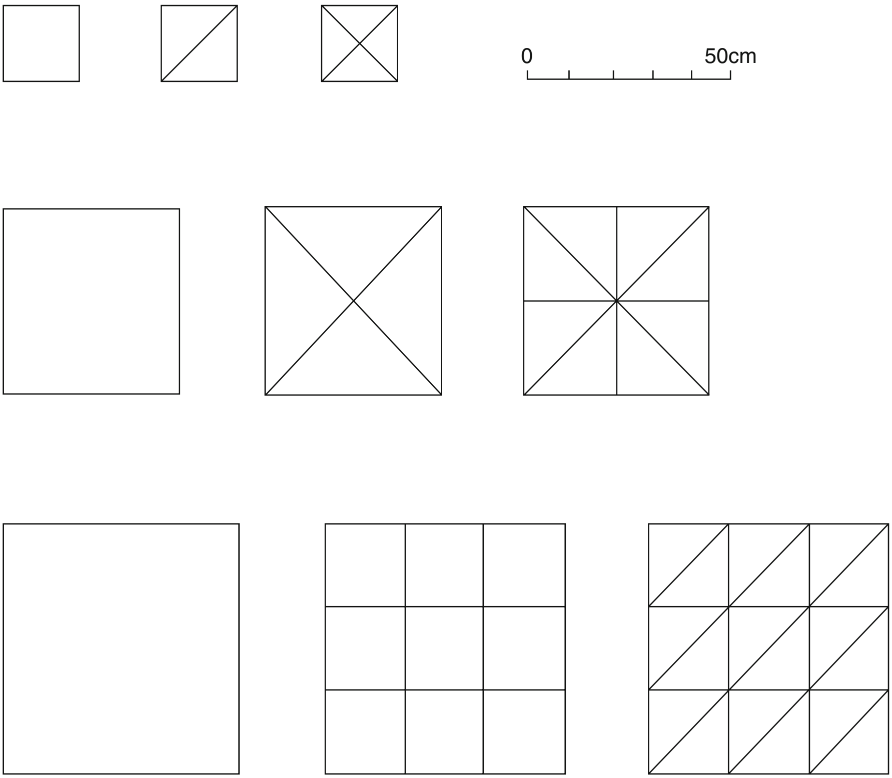

Fig. 12.4 The methods used for obtaining triangular bricks starting from square bricks. From the *top*: bessales (2 / 3 of a foot), sesquipedales (1.5 feet)

The availability of large amounts of dust and small pieces of bricks created by the cutting of bessales and sesquipedales probably contributed to the spread of *cocciopesto*.

A brick's mechanical properties depend, aside from those of its raw materials, on the temperature at which it is fired. There was the over-fired type, the well-fired (the best) and the light-coloured (under-fired) types, all depending on the levels in which they were placed in the kiln.

On average, a brick's compressive strength (load factor) is between 15 and 20 MPa (N/mm^2), and sometimes up to 30 MPa. Increasing temperature leads to an improvement in mechanical properties as well as a resistance to wear, due to the increased formation of silicate crystals.

Since it was uneconomical to transport bricks over long distances, brickworks were placed as close as possible to where the bricks were to be used, or near river transportation, to facilitate the supply of the necessary clay, water, and wood.

A typical brickworks had basins for the refining and working of the clays (to correct them or knead them to improve their plasticity), a kiln (or kilns) and covered areas for drying. Undoubtedly the kiln was the most technologically interesting part of the whole production process.

Normally rectangular or elliptic, kilns had a central combustion chamber positioned on their main axis and (usually) below ground level. The floor of the kiln, supported by columns and arches, with holes to allow for the passage of heat, was above the combustion chamber. The bricks to be fired were stacked on this floor.

Aside from the evolution of production and firing techniques, the stamping of bricks (Adam 1988; Zaccaria 1993) before firing, starting in the late republican period (and continuing until the emperor Theodoric), was a further indication of the Romans' bent for industrial and commercial organization. Initially, this practice was only adopted for more valuable ceramic products. Stamps were sometimes used following imperial decrees.

The shape of the stamps and the information they contained varied depending on the period and the product. In their most complete form they carried the following information:

- the name of the owner (*dominus*) and the land (*praedia*) from which the clay came;
- the person in charge of production (*officinator*);
- the name of the producer and kiln (*figlinae*);
- the consular date;
- more rarely, the type of product.

Commercial relations were probably regulated by a contract in which the *dominus* required the subcontractor (*conductor*) to produce a certain quantity of bricks for a specified sum. The product thus remained the property of the *dominus* who was usually a member of the senatorial class, while the *conductor* might be a slave or freedman (or even a citizen).

There is documentation regarding nine kilns in the Rome area during the period 80–97 A.D. and 29 kilns during the period 98–113 A.D. Probably there was more than this. It is certain that clay was quarried in the areas of Trastevere, the Vatican, along the Via Salaria and in the Tiber valley and other sites can be guessed at from the names of the *praedia* (Amici 2005).

Production rates were normally related to building booms and to the undertaking of important projects.

12.4.2 The Bricks in the Basilica of Maxentius

The Basilica of Maxentius, a colossal edifice, was built in the space of only a few years at the beginning of the 4th century, as mentioned earlier. This undoubtedly implies a well-organized programme for the supply of building materials.

Construction began after a lull in the building industry, relatively stagnant after Caracalla, with the exception of the building of the Aurelian walls. The new building boom started with Diocletian. The bricks used to build his baths have three types of stamps, but are all from tetrarchic imperial factories and thus made specifically for the occasion. The same situation, though much less well-documented, is repeated for the Basilica of Maxentius. Aside from a fair number of stamped bricks from the periods of Domitian and Trajan-Hadrian, probably from the Horrea Piperataria, we found only two bricks with different stamps, perhaps Constantinian (CISTeC 2001).

Wishing at this point to make some quantitative considerations, let us look at the volume of materials used in the Basilica. The volume of the foundations, significant both for extent and depth, is about 8,500 m^3, while the walls and vaults occupy 39,000 m^3. The total surface area of the walls covered in brick-work is about 11,300 m^2.

On average a square metre of wall surface of the Basilica contains 70–80 triangular bricks (16–18 rows) each averaging about 20 cm in length and about 3–4 cm in thickness. The total number of bricks needed was around 850,000.

The arches at the ends of the large barrel vaults needed a total of 4,300 bipedales, while those used in the smaller arches and the other walls (up to 8–10 m above floor level) may be estimated to be about 12,500.

Based on the information found in the Italian edition of J. Claudel's engineering manual (Claudel 1852), we can attempt to estimate the amount of wood needed to fire the bricks and roast the lime. Indeed, at that time the techniques employed were still very similar to those used by the builders of ancient Rome.

One kilogram of wood was needed to fire an ordinary $5 \times 12 \times 24$ cm parallelepiped brick in a wood kiln. We can estimate that about the same amount of wood was needed to fire a bessale measuring $3.5 \times 20 \times 20$ cm. It therefore took half a kilogram of wood for a triangular brick. Estimates for firing the much larger bipedales are uncertain; we can estimate that 8 kg are sufficient. Thus $11{,}300 \times 75 \times 0.5 = 423{,}750$ kg of wood needed to fire the bricks and $16{,}800 \times 8 = 134{,}400$ kg of wood for the bipedales. In total, about 560 t of wood.

As regards production, we can estimate that a worker with at least two assistants (one to prepare the clay and the other to position the bricks for drying) could shape about 1,000 bricks per day working in the period from May to September, about 150 days a year. In fact, there is evidence from the first half of the last century (archives of the Giavarini Brick works in S. Secondo, PR), in which a family of husband, wife and two children produced more than 1,000 roof tiles in a single day (Fig. 12.5).

As such, a team of workers could produce about 150,000 bessales in a year. After these were divided, the number of semilateres was double this.

12.4.3 The Mechanical Properties of the Bricks in the Basilica

The tests carried out at the Faculty of Engineering of the University of Rome "La Sapienza" (Giavarini et al. 2006) have shown that the range of resistance to compression of the samples tested was extremely wide, from a minimum of about 8 to a

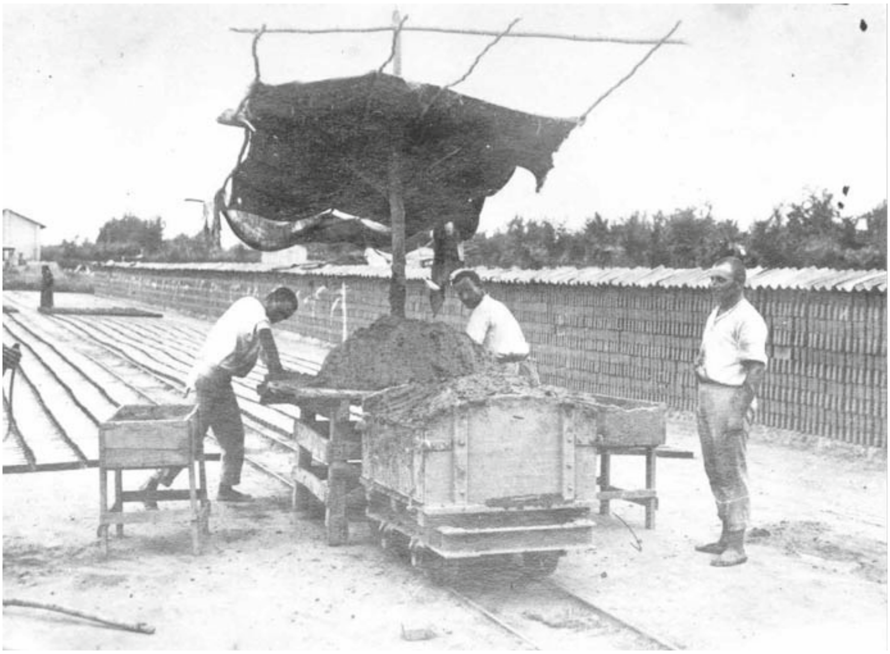

Fig. 12.5 Manual preparation of bricks in the earlier 1900s. The techniques and organization of the work are similar to those used by ancient Romans (Giavarini Brickworks, S. Secondo PR)

maximum of 37 MPa, with a clustering of values around an average of 22 MPa. Due to the difficulty of collecting material from a historical monument and then destroying it, these tests were carried out on only 30 samples. If we compare these figures with those for modern industrially produced materials, they are relatively low. In fact, the material was not homogeneous, with grains measuring up to 1–2 mm and a porosity of up to 22 vol %. The average value of the elasticity module was about 13.4 GPa.

Ductility, measured as the ratio of post-collapse deformation at 50% compression to peak deformation, had an average value of 2.25, so the material was relatively fragile.

There are no systematic experimental results for bricks from the Roman period; however, though these values were not high, they were comparable to those measured by CISTeC on other occasions. The wide range of results is an indicator of both different firings as well as different levels of care taken during preparation of the material.

However, comparing the resistance of the bricks with those of the mortar, we see that the mechanical values of the former are not particularly influential compared with the actual structural element, in other words the concrete; this is true especially for the very thickest walls, in which the contribution of the outer brickwork becomes truly negligible.

12.5 Binders and Mortars

12.5.1 Lime, Lime Putty and Quick Lime Mortars

Already well-known in the Middle East in early antiquity, at that time lime was used mostly for plaster and paintings. The ancient Greeks also used lime to prepare stucco and painted plaster. However, it was the Romans who introduced its systematic use as a binder in spite of clay. Later, probably as early as the 3rd or 2nd century B.C., the Romans introduced developments that were fundamental in "perfecting" concrete (Giuliani 1998).

Lime (*calx*) is produced when limestone (calcium carbonate) is heated to 800–900°C. Calcium oxide (quicklime) and gaseous carbon dioxide are formed, creating white, friable lumps (*glaebae*).

Due to the irregular distribution of temperature in ancient kilns, some of the limestone was not entirely decomposed and some was dead burned, forming compact, sintered lumps that only hydrated slowly and with great difficulty. During the following phase, when the lime was reacted with water, attempts were made to eliminate these defects (e.g., using sieves).

The initial violent reaction with water increased the volume of the lime significantly, transforming it into a sticky, plastic white paste (*calx macerata*, today known as lime putty). In general the water content was over 50%. To be of good quality, the lime (above all "lime putty") had to be aged for several months in special earth-covered trenches (Vitruvius).

In contact with the atmosphere, lime slowly absorbs carbon dioxide (about 0.03 vol % of the atmosphere is composed of CO_2) changing back into carbonate. The evaporation of the water leads to a significant reduction in volume, with the formation of an incoherent material without any resistance.

Due to its poor mechanical properties, lime by itself is only used in very thin layers and to prepare surfaces for paintings. Adding an aggregate such as sand (two or three times the volume of the lime putty), improves its mechanical properties and a quicklime mortar is obtained. In this way shrinkage is limited and the lime is better exposed to carbonization by the atmosphere. However, because of their porosity, lime mortars cannot guarantee high levels of resistance. They were in fact used on surfaces rather than for structural purposes.

Depending on the oxide (and magnesium) content of the lime, mortars are classified as "fat" (*calx pinguis*) or "lean" (*calx macra*). Fat limes come from purer types of limestone. They are more plastic and make better mortars. Lean limes come from limestone containing impurities or poorly (either insufficiently or excessively) burned limestone. During quenching they absorb less water and do not swell as well. Other impurities (e.g., iron compounds) tend to darken the lime, which takes on a greyish rather than white colour.

Marble was widely used (especially in the empire) to produce lime because it was practically without impurities.

Table 12.1 Composition of Roman mortars according to Vitruvius

Lime	Aggregate	Water*
One part	3 parts of quarried sand	15–20%
One part	2 parts of river or sea sand	15–20%
One part	2 parts river sand and one part crumbled brick	15–20%
One part	2 parts poz zolana	15–20%

* The quantity of water depends on the lime putty, the climate and the use to which the mortar will be put

12.5.2 Pozzolanic Mortars

The need to increase the poor resistance of quicklime mortars and improve hardening, even in water (e.g., for the construction of support foundations for bridges and aqueducts) led Roman builders to develop mortars containing pozzolana or other materials which behaved in a similar way (e.g., brick dust): these were the forerunners, by more than 2,000 years, of a material similar to today's Portland cement.

The term *pulvis puteolanus* was used by the Romans for an incoherent material found in the Pozzuoli area, but also common near Rome in the Alban Hills. Pozzolana contains a high proportion of reactive silicates (40–70%) and originated from explosive volcanic eruptions. The particles of magma carried by the gases underwent a strong quenching that transformed them into a vitrified mass which is particularly reactive with lime hydrate.

The ability to fix lime is possessed to a lesser degree by other materials as well, such as pumice and fired clays (well-fired bricks, e.g.). The silica and reactive alumina found in materials with pozzolanic activity react with the lime and water to give a composition very similar to that of modern cements. It was due to this ability to fix lime and form hydraulic cementing composites (i.e., capable of reacting even when immersed in water), that pozzolana was so widely used by the Romans for construction.

The recipes for preparing good mortar are given by Vitruvius and other authors. Table 12.1 contains a summary of Vitruvius' recipes, confirmed by the analysis of various mortars from Roman times.

The quality of Roman mortars is attested, for example, by the remains of a mausoleum located near the Villa of the Quintili on the Via Appia. Much of the structural material has been removed, especially at the base; in spite of this, the mausoleum remains standing like a monolith, notwithstanding the disturbing overhang around the base (Fig. 12.6).

12.5.3 The Mortars Used in the Basilica of Maxentius

12.5.3.1 Composition

The chemical and physical properties of the mortars used in the Basilica will tell us something about their quality, resistance and origin, and thus contribute to the

Fig. 12.6 The image of the remains of a mausoleum near the Villa of the Quintili (Appia Antica) showing the exceptional resistance of Roman *opus caementicium*

historical study of the monument itself. Examining the chemical analyses of the mortars employed in the Basilica of Maxentius (at least those thought to be from the Maxentian or Constantinian periods) we find that they contain 19–27% of calcium carbonate. This corresponds to a weight ratio of lime to pozzolana between 1:6 and 1:4. The mortar richest in lime (1:4) was used in the vaults, while the poorest (1:6) was used in the vertical structures.

This is confirmed by the analyses carried out by CISTeC on samples taken from the core of a large fragment of the vault lying on the ground, where the structure has been preserved to its full depth, from the internal coffering to the mortar on the other side with the imprints of the roof tiles. In fact, the analysis of these mortars has highlighted their high calcium carbonate content (25–27%), an indicator that in the vault the ratio of lime to pozzolana was higher. The pozzolana used in this area was always the red type, i.e., the highest quality. We can conclude that, in general, the mortars in the original parts of the monument were of excellent quality.

The same cannot be said for those parts of the monument which were subjected to later interventions. We might take as an example the wall facing the Colosseum.

This has suffered surface wear, with both the crystallization of mineral salts and biological phenomena with the colonization on the surface of algae and lichens. It is highly improbable, however, that this surface deterioration has penetrated deeply enough to cause any weakening of the structure.

The mortars for surface finishing required higher plasticity and those analysed showed, as one might expect, higher calcium-carbonate content between 30 and 35% corresponding to a weight ratio of lime to pozzolana between 1:3 and 1:2.5.

Of the 30 samples contained pozzolana, 24 red pozzolana and only 6 brown pozzolana. The different colour of the mortars made using brown pozzolana almost always indicates a different period from that of the Maxentian-Constantinian phases of the Basilica, when only red pozzolana was used.

Red pozzolana is found in almost every sample taken from areas thought to have been built under Maxentius or from modifications carried out under Constantine. The mortars from earlier constructions (by Nero or Trajan) were all in red pozzolana as well. Evidently, these were all buildings for which the highest possible quality of mortar was required.

Almost all the mortars analysed indicate the presence of some gypsum. The highest gypsum contents (up to 13 wt %) were measured in the mortar from the collapsed vault. The presence of gypsum in the mortar poses a problem of interpretation, because the quantity found is very high and it is difficult to attribute it to sulphate formation from atmospheric pollution.

It is possible that gypsum was used to accelerate the setting of some of the mortars in the Basilica, but hitherto we have found no historical information or scientific data allowing us to reach any definite conclusions regarding this. A comparable problem emerged in the past with the mortars from the Markets of Trajan, where the gypsum content was even higher.

We might suggest that the extensive presence of decorative plaster in the interior parts of the monument could be the cause of this. Over time the gypsum might have dissolved, spread into the thickness of the wall and then re-crystallized.

12.5.3.2 Mechanical Properties of the Mortars

Considering how it was used and the thin layers available, it would not have been easy to remove samples suitable for physical and mechanical measurements. Therefore, mortars of “Roman type” were reconstructed in the laboratory.

Test samples (40 × 40 × 160 mm) of lime mortars were prepared with powdered quicklime, due to the difficulty of preparing lime putty in accordance with ancient Roman methods.

The quantities of *harena* used were based on Vitruvius. We decided that he used this term to mean pozzolanic material from quarries near Rome, referring to it as sand. The term *pulvis puteolana* by contrast was probably used only to indicate the finer volcanic ash which really did come from Pozzuoli.

We used one part of lime to three parts of pozzolana (from Pomezia) and 1.4 parts of water in volume. The weight ratios were respectively 1:2:1.11.

The mechanical resistance values obtained after curing these samples for various lengths of time were far higher than those required by modern Italian regulations for masonry. The resistance to compression was 9 MPa, as opposed to the 2.5 MPa of modern Italian regulations. The ductility was also much higher. Elastic deformability was about one tenth that of modern concrete.

12.5.3.3 Some Quantitative Considerations

If we look at the amount of mortar used to prepare the concrete for construction when the Basilica was built, we find that this varied from one area of the building to another depending on local function and structural needs, but was always between 40 and 60 vol.% of the concrete.

Considering that, as we have seen, the volume of the masonry is 47,500 m^3 and assuming that on average 50% of this is mortar, we find that the amount of mortar used in the construction was a little bellow 24,000 m^3.

The amount of lime (if we accept the ratio of 1:4) is therefore 6,000 m^3. In the aforementioned manual by Claudel (1852), we find that 800 kg of wood are needed to produce one cubic metre of lime; the amount of wood burned was thus about 480 t. These simple calculations indicate how "energy intensive" the construction industry of Roman times must have been, and at the same time, how environmentally unfriendly it was.

12.5.4 Plasters

A general rule for buildings in the classical period is that plasters were always richer in calcium carbonate than the mortars used for masonry. This rule is confirmed by the Basilica of Maxentius. In the samples of surface finishing (decorations and fake marble) removed from the fragment of the collapsed vault and coffering and analysed, there was a gradual increase in calcium carbonate, with the highest levels being reached in the fake marbles, which contained up to 94.7%. This high $CaCO_3$ content derives from the minute fragments of marble (almost pure calcium carbonate) mixed with the lime. Red pozzolana is present, but only barely.

12.6 The *Opus Caementicium* for the Basilica

12.6.1 How Opus Caementicium was Made

From an etymological point of view, the word *caementum* was used to refer to pieces of stone joined by a binding substance in masonry constructions. It indicated neither the binding material nor the concrete, which was described by Vitruvius as a "structura ex caementis calce et harena; genus pulveris (pozzolana) mixtum cum calce et caemento".

Perhaps no other invention by Rome's engineers has had such a profound influence on the modern world as concrete. Without it there would have been no basis for virtually any of the developments of the modern building industry. The Roman concrete was used on its own for foundations, either in open excavations or in wooden moulds or formworks. However, it was most commonly used to fill the space between two facing walls composed of elements different from it, e.g., truncated pyramids of tufa (*opus reticulatum*) or triangular sections of brick (*opus latericium*) (Fig. 12.7).

Normally the *caementa* (pieces of tufa, brick, marble, stone, etc.) were set by hand with the largest surfaces being placed horizontally, with regular pounding to increase compactness and thus the final resistance. In all cases, vertical alignments, that could lead to the formation of cracks, were avoided.

In practice, the construction phases for a masonry wall were as follows:

- building the two layers of the facing walls, sometimes with external supports;
- pouring in a layer of mortar;
- insertion of rough pieces of aggregate;
- pounding to increase compactness;
- construction of an upper layer of facing walls, with possible insertion of transversal tying elements and so on.

Where possible, the work proceeded maintaining the wall at the same height for the entire perimeter of the construction, so that it settled in a uniform way. The workers

Fig. 12.7 *Opus caementicium* contained within two facing walls of triangular bricks (*opus lateritium*)

had to stop at regular intervals to allow the concrete to complete its initial hardening so that the wall was ready for the increased load of the next layer. The triangular bricks of the *opus* were placed in alternating rows so that they did not line up creating vertical joints; moreover, in this way they provided a good bond with the mortar of the concrete core.

Sometimes, in very thick walls larger bricks were used in place of cut triangular ones. This was to avoid excessive weight pushing against the facing walls during construction and before the final hardening of the concrete.

A significant amount of tufa material in the *caementa* may cause dimensional variations in the presence of humidity (Giavarini and Santarelli 2001). Tufa contains zeolite, a compound which can absorb (and release) water and if humidity levels are sufficiently high, this expansion may cause cracking.

12.6.2 Mechanical Properties of the Concrete in the Basilica of Maxentius

The actual support offered by a facing wall of *opus latericium* composed of triangular bricks (e.g., square bricks measuring 20 cm cut diagonally and set in alternating courses) was in practice only about 7 cm.

If this thickness is significant for walls about a foot thick, it is negligible when they are 4–5 m wide as in the load-bearing walls of the Basilica of Maxentius (the 14 cm of the facing walls is less than 3% of the thickness of a wall, which is 500 cm wide). The obvious conclusion is that, to evaluate the strength of a large Roman monument, it is necessary to have a sufficient knowledge of the mechanical properties of the concrete. Compared to the amount of mortar, the percentage of aggregate in concrete is usually relatively low.

As seen earlier, we can estimate that the concrete in the Basilica of Maxentius is composed of 40–60% of mortar. The lowest percentages refer to the areas where the building of the concrete structure was done most carefully. By comparison, modern concrete has an average mortar content of about 33% (i.e., 1/3 sand and cement and 2/3 pebbles or gravel).

Taking samples of ancient concrete is not easy, since, understandably, those responsible for the monuments are opposed to materials being removed from them. Furthermore, the material is almost never isotropic. The aggregate, both natural (tufa, travertine, basalt, or pumice) and the pieces of brick are usually stratified perpendicularly to the compression, i.e., horizontally. It is obvious that the workers whose job it was to prepare the *caementum* must have had at least a minimum of specialized training. This layering means that the sample must be tested along an axis perpendicular to the stratification itself. This makes the task of collecting a sample even more difficult, since the samples collected for the tests must be orthogonal to the stratification of the structure. Fortunately, we were able to take suitable mortar samples from the terrace floor of the Basilica during repaving and waterproofing works; other samples were taken from the wall of the third vault and from the foundations on the side facing the Via Sacra. The results of the technical tests are given in Table 12.2.

Table 12.2 Mechanical resistances of samples from the Basilica of Maxentius

Location of sample	Type of sample	Apparent density (kN m^{-3})	Resistance to compression (MPa)	Modulus of elasticity (GPa)
Terrace floor support	Core Φ 150	13.4	2.35	–
Terrace floor support	Core Φ 150	13.5	2.43	–
Concrete from third vault	Core Φ 150	15.4	6.07	–
Concrete from third vault	Core Φ 150	14.8	4.97	–
Concrete from third vault	Core Φ 150	15.0	5.82	–
Concrete from third vault	Core Φ 150	14.6	4.84	–
First wall	Prism 350 × 350 × h	–	6.0	2.80
Second vault	Prism 350 × 350 × h	–	4.2	1.75
Foundation, first vault	Prism 350 × 350 × h	–	5.3	3.50
Thief's arch	Core Φ 150	16.5	6.16	–

The series of tests carried out on the mortars demonstrate that the resistance to compression is in line with the results obtained by Rondelet (1834) at the beginning of the 19th century. The results proposed by Lamprecht (1968), giving much higher values (a maximum value above 40 MPa) are difficult to accept.

Another important aspect is that the quality of the concrete tends to improve when the structural element to which it belongs was placed so that it would be submitted to higher stress levels. Due to the high proportion of mortar, between 40 and 60%, the quality of the concrete depends mainly on the mortar. Higher percentages of aggregate give the *caementicium* higher levels of resistance. As far as the Basilica is concerned, bearing in mind the damage caused by sampling (by coring or using a chain saw and then reshaping the sample), we can normally count on a resistance of 5–6 MPa and an elastic modulus of 3 GPa.

12.7 The Cocciopesto

Cocciopesto (*opus testaceum, testaceum corium, inpensa testacea*) is a mixture of lime, sand and/or pozzolana and chips and powder from bricks. It has excellent hydraulic properties, conferred upon it both by the pozzolana (when present) and by the crumbled brick which, mixed with the lime, has both pozzolanic and hydraulic properties.

Reacting slowly with the lime, the alumina-silicates of the bricks form composite hydrates that fill the spaces in the mortar, making it less porous and more impermeable. This is why it was used in waterproof lining for basins, aqueducts, and other structures. After pouring it was pounded to thicken it and reduce the number of empty spaces. Due to its long presence in extremely humid conditions, it also developed a high mechanical resistance to traction.

Though it was often used in thin layers, *cocciopesto*'s mechanical qualities make it a real conglomerate (i.e., concrete with fine-grained inert material).

One testimony to the exceptional mechanical properties of *cocciopesto* can be found in the great cistern in Atri (Giuliani 1998). The layer of *cocciopesto* was poured over a clay base, which was later washed away. The layer of *cocciopesto* forming the floor passed from being subjected to compressional to flexural loads without showing any signs of collapse. In some cases the resistance to compression of *cocciopesto* paving exceeds 10 MPa.

In the Basilica of Maxentius *cocciopesto* was used on the extrados of the terraces. Portions of *cocciopesto* were found during waterproofing work on the extrados of the surviving side nave and on the extrados of the portico facing the Colosseum.

12.8 The Use of Stuccos by the Romans

As in other Roman buildings, here too the stucco decorations formed part of a single architectural scheme and was not a later addition. Speaking specifically about the Basilica of Maxentius, if we add to the famous stuccoed coffering of the existing vaults that of the collapsed naves and apse, the total linear extension of the stucco decorations is about 12 km! (Monaco 2001).

Broadly speaking, a stucco is a fine mortar, composed of a binder and powdered aggregate, which can be moulded and smoothed. The binders available in Roman times were lime (mostly) and gypsum, or a mixture of the two. The aggregate used could be powdered marble, travertine or brick or pozzolana. With thin layers of this material, applied on backings of hydraulic mortar, the Romans created fake marbles or surfaces that could be given coloured decoration.

This was a patient art in Roman times and still is: the creation and application of a workable, compact, correctly thixotropic paste, which maintained its form regardless of its weight and could (once hardened) be polished and painted.

The various techniques used to make and apply stucco all agree on the need for care in the preparation of the base material, above all the lime putty. In this case, the important problem is the presence of the non-quenched particles (*calcinaroli*) or granules, the stucco-worker's nightmare. In practical terms, this meant that the quenching period for stucco putty was much longer than for normal lime putty.

The need for a very white product (e.g., when it was necessary to imitate marble) meant that the limestone chosen to produce the lime had to be extremely pure. The mixing and homogenization of the powdered material (done by hand) was time-consuming, tiring and involved grinding it with a mortar and pestle.

The most difficult types of stucco to apply were projecting cornices, high relief and ceiling and vault decorations. In these cases it was necessary to create a lower layer of pozzolanic mortar and frame able to support the stucco. The stucco had to resist not only the static load of its own weight but also any action deriving from wind, earthquakes, cleaners, etc. Vitruvius mentions the addition of pins and/or nails to support stucco decorations and we find these used in the Basilica as well.

12.8.1 Stucco Decoration in the Basilica of Maxentius

The *lacunari* (from the Latin *lacuna*, empty space), that is the coffering in the vault, constitutes perhaps the most characteristic of the decorative elements in the Basilica of Maxentius. It is primarily composed of large (110 cm per side) concave octagons set into the vault (Fig. 12.8). Between the octagons there are smaller concave shapes. The inner concavity of the *lacunari* is obtained by the presence of three steps, each forming a progressively smaller octagon.

The three surviving halls of the Basilica contain 180 octagonal coffers. The total length of the stuccowork around each octagon is about 17 m (Monaco 2001).

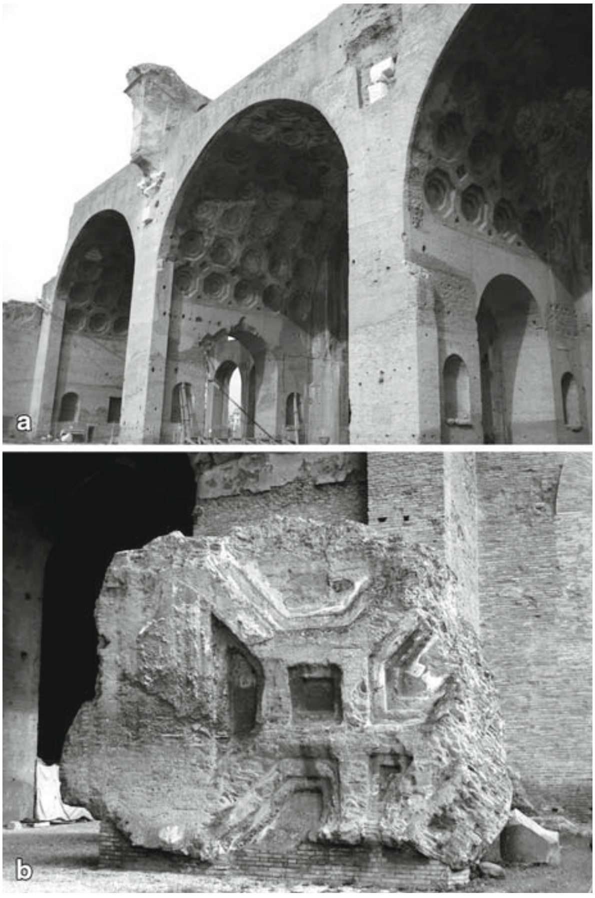

Fig. 12.8 The coffering of the Basilica: **a** view of existing arches; **b** view of a fragment on the ground

If the surviving ones are added to the those from the missing parts of the Basilica (the central and other side nave and apse) we can estimate that the total linear stuccowork around these would reach 11–12 km, this without counting any other decorations, many of which we probably do not even know about. Due to these impressive figures and the speed with which the Basilica was constructed, we must assume that there was a well-organized work plan, involving a “production line”. The first phase, during the construction of the vault, was the application of the wooden mould to “mould” the concrete into the shape of the three-stepped octagons.

From floor-level the vaults appear extremely regular and harmonious and this is the effect the builder was trying to achieve. On closer observation though, it can be seen that there are a number of geometrical irregularities, which were probably due to either imperfect carpentry or the deformations caused by pressure from the weight of the concrete as it came into contact with the moulds. It is probable that several dozen moulds were used simultaneously when the concrete was poured.

Irregularities can also be seen (once again only through closer observation) in the stucco decorations. If we consider both the aforementioned linear extent of the stucco decoration, and the speed with which the building was constructed, we are led to think that there may have been prefabricated models (strips or “sticks”) produced on the ground in series using a basic pattern and then attached to the surface of the concrete with binding mortar and perhaps with nails. The various models were adapted in loco with more or less obvious variations from the original project design. These adjustments were concealed by remodelling the cut parts and then by filling and homogenizing the whole. A final coat of liquid stucco covered the cuts and later also formed the support for the painted decorations.

The gigantic construction project for the Basilica, involving an extremely large number of people, must necessarily have been divided up into secondary work areas for, apart from the structure itself, the stuccowork, the marbles and the other decorative elements. The various parts of the construction site were supplied regularly with all the necessary building materials, this without counting the workers’ food and other aspects of supply. Even today, the organization and coordination of such an undertaking is astounding.

12.9 The Marble Used in the Basilica

The floor of the Basilica and all the interior walls, up to the arc of the vaults, were covered with marble slabs. Today the only traces of these are the prints they left on the mortar in which they were set. A conservative estimate of the total surface area is 12,000 m^2, i.e., more than a hectare. Considering that the average slab was about 5 cm thick, and that marble weighs on average around 2,700 kg m^{-3}, we can deduce that the total volume was about 600 m^3 and the total weight around 1,600 t. All this implied a substantial economic outlay and an extremely efficient organization for supplying, transporting and managing such an enormous quantity of valuable materials.

12.9.1 The Main Types of Marble Used in the Basilica

Below is a brief list of the main types of marble used in the decoration of the Basilica, of which traces have been found. Some of their distinctive characteristics are also noted. Figure 12.9 shows the areas from which these marbles originated (Pensabene 1994).

Lucullan (*africano*)—a breccia marble which is difficult to work, from quarries at Teos in eastern Turkey. It was among the first to be brought to Rome for use in columns. It is frequently used in Latium, but otherwise is uncommon. It is rarely mentioned in documents after the Antonine period, but was still named in the Edict of prices under Diocletian (40 *denarii*).

Carystian green (*cipollino*) comes from Euboea, Caria, and Cyprus. Its Italian name derives from its similarity in appearance to sliced onion. It was extremely widespread and was used in Rome from the time of Caesar.

Numidian yellow shows compact, very fine-grained fabric with extremely varied gradations. It was quarried from the quarries of Chemtou in Tunisia. It was used in Rome in the 2nd century B.C., the most widespread use dates between Augustus and the Severans. It was rarely used after the 3rd century A.D. This stone type is very rare in Africa and is scarce outside Italy.

Grey Egyptian granite (*granito del foro*) was widely used in Rome's imperial forum and comes mostly from Egypt and Turkey. It could be worked in large pieces and was very solid. It was documented from the Flavians on.

Fig. 12.9 Map showing the areas from which the marbles used in imperial Rome originated

Phrygian purple (*pavonazzetto*) has compact fabric, medium-grained rock fabric. It was transported from the quarry of Docimium in western Turkey. It was introduced to Rome very early. It was used for the whole imperial period throughout the empire. It was among the most expensive in Diocletian's Edict of prices (200 *denarii*). It was used for numerous purposes: paving slabs, columns and also for wall coverings.

Chian pink/grey (*portasanta*) marble takes its Italian name from the fact that in the 16th century it was used for the door jambs of St Peter's. From the island of Chios, it is red-grey, compact, homogeneous and easily worked.

Red porphyry originated from the Gebel Dokham quarry in Egypt. It reached its maximum use under Diocletian and up to the 5th century A.D. The stone was well-known throughout the Roman empire from the 3rd century A.D. and was probably used in Rome by Augustus. From Trajan's reign onwards it was reserved for the imperial family.

Proconnesian is coarse-grained, white but tending to grey, with a uniform tonality. It has a good resistance to atmospheric agents. It was widely used throughout the Mediterranean basin from the 1st century A.D.

Green porphyry (*serpentino*, *Lapis lacedaemonium*) comes from quarries near Sparta. It was probably used in Rome from Augustan times. It was extremely widely used in the Flavian period but continued to be popular well into the Byzantine period. It is quite difficult to work. It was only used for relatively small features.

12.9.2 The Paved Area and the Wall Area

The paved area, certainly damaged by the collapse of the vaults, has suffered progressive and irreversible damage due to the various uses of the building in modern times, first as a corral for cattle, then as a riding school and later, in 1848, as a military training camp for the French army; finally, with the removal of all the remaining slabs of marble during the "cleaning up" of material which had collapsed during the 19th century. We are certain of the geometric pattern of the floor. This consisted of quadrangular slabs with central patterns composed of circles and lozenges, framed by bands around the perimeter. The only important differences were in the northern apse, created slightly later and in the eastern portico.

It is not equally easy to determine the types of marble used for each single element of the decorative pattern. The use of Numidian yellow, Lucullan black/red, Carystian green, green porphyry and Phrygian marble are documented (Fea 1819). The supporting surface on which the slabs were laid consisted of layers of mortar with fragments of marble to make it flat. From the extremely fragmentary remains of the slabs, and the imprints left by others in the mortar, we can deduce that they were between 3 and 8 cm thick.

The pattern of the wall decoration can be reconstructed from the holes in the walls left by the iron clamps used to hold the slabs of marble in place, but we cannot identify the types of marble used with any certainty.

The fragments of marble slabs found in the early medieval dumpsites in the area of the north apse are eloquent testimony to the relative percentages of marbles used: Numidian Yellow (50/70%), White marble (20/40%), Phrygian marble (8/10%) and porphyry, Chian pink/grey and green porphyry each between 6 and 8%.

With very few exceptions, such as some of the brackets in the northern apse, from the second phase, most of the marble architectural elements in the Basilica seem to have been reused (Carè 2001); following a practice that had been widely adopted for over a century these were reworked and adjusted to present a whole that was as coherent as possible. Furthermore these were virtually all in Proconnesian marble, except for a very few in Pentelic marble.

The uniformity of the decorations on all the external façades—stucco-decorated plaster designed to resemble squared blocks in a homogeneous greyish-white colour—accentuated the visual impact of the ornate polychromatic decoration of the interior, widening its spatial boundaries and multiplying its expressive possibilities. Furthermore, the choice of grey granite for the diaphragm columns of the northern apse (in contrast to the wall and flooring slabs of the interior), and of red porphyry for the columns of the main façade facing the Via Sacra (which stood out strongly from the uniformity of the plastered wall), demonstrates a refined and knowledgeable management of the potential offered by a careful evaluation of chromatic effects (Fig. 12.10).

Fig. 12.10 Virtual reconstruction of the façade of the Basilica facing the Via Sacra. There is no evidence for any specific shape for the cornices over the colonnades, so they have been made as linear as possible

12.10 Conclusions

The study conducted by CISTeC on the construction materials and techniques of the Basilica of Maxentius has been the occasion for gaining a wider insight into the properties of the building materials used by the Romans. It is still astonishing how the Romans could produce in a short time industrial quantities of building materials whilst maintaining a high and constant level of quality.

The brick making was a real modern industry which created and used techniques still valid till the half of the last century; size and stamping of bricks were standardized.

But the most important invention of the Romans was the *opus caementicium*, that is a real precursor of the modern cement concrete (Portland), which dates backs to the end of the 19th century. Without such invention there would have been no basis for virtually any of the developments of the modern building industry. The high strength and resistance to water (and environmental agents) of the concrete was due to another invention of the Romans: the mortar made by mixing high quality lime and pozzolana. In fact, due to the high proportion of mortar, the quality of concrete depended mainly on the mortar. Very large-scale construction projects like the Basilica of Maxentius depended on a perfect organization of the building site and on a regular supply of materials, especially when the construction schedule was very tight. In most cases the most important Roman buildings did not collapse due to constructions defects or poor materials, but because they were abandoned after the fall of the Empire and pieces were removed for reuse in other buildings.

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Chapter 13
Characterization of Ancient Pozzolanic Mortars from Roman Times to the 19th Century: Compatibility Issues of New Mortars with Substrates and Ancient Mortars

Ana Luísa Velosa, Rosário Veiga, João Coroado, Victor M. Ferreira and Fernando Rocha

13.1 Introduction

The use of pozzolanic mortars is widespread, as natural pozzolans coming from South America to Europe and Japan were often incorporated in lime mortars to ensure a pozzolanic reaction and enable the capability of mortars to harden under water (Heikal 2000; Holmes and Wingate 1997; Moropoulou et al. 1998). Their use was especially prominent during the existence of the Roman Empire, when *opus signinum* mortars were used throughout the occupied territories, wherever there was a lack of natural pozzolans; there is evidence that similar mortars incorporating crushed ceramics were employed in other locations such as Syria (Ingo et al. 2004) or Turkey (Degryse et al. 2002). Pozzolanic mortars continue to be used nowadays and examples of current applications of lime and crushed ceramic mortars are Surkhi in India and Homra in Egypt.

The use of pozzolanic additions in mortars has a long tradition, relating to the necessity of producing mortars capable of hardening under water. In the Roman Era, mortars containing natural pozzolans of volcanic origin were frequently used in water-bearing structures such as tanks, aqueducts and dams. In regions with no available natural pozzolans, crushed ceramics (*cocciopesto*), probably derived from waste, were used, producing mortars with a pink colouring designated as *opus signinum*. More than just protecting walls from water penetration and damp, these mortars also attained great durability, as in archaeological sites they still present a generally good appearance and at least apparent adhesion and strength. Pozzolanic additions continued to be used throughout the centuries and this is documented by various authors (Bruno 2005; Casa Commercial Oliveira Machado 1867; Castanheira das Neves 1906; Cleto 1998; Colella et al. 2001; Santos 1975). In Portugal,

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apart from the extensive application of *opus signinum* in baths and tanks during the Roman Era, pozzolanic materials are known to have been used in fortresses during the Islamic occupation of southern Portugal (Bruno 2005) and in the 19th century in maritime structures and other constructions (Casa Commercial Oliveira Machado 1867; Castanheira das Neves 1906; Cleto 1998). However, it is possible that these materials were of current use at all times, although there is no known documentation that supports this.

The existence of pozzolanic mortars in Portugal linked to Roman occupation or to natural pozzolanic resources from the volcanic islands of Azores and Madeira, together with the durability attained by these mortars led to a study aiming at their characterisation. For this purpose, mortars from different centuries were sampled and analysed, taking into account chemical, mineral, physical and mechanical characteristics.

Conservation practice applied to renders must take into account the preservation of the existent wall/render system. Hence, compatible mortars must be designed to repair or, whenever needed, partially substitute ancient renders, in order to attain an adequate performance in terms of mechanical, physical and chemical properties. The compatibility concept includes functional and aesthetic issues: the new mortars should not accelerate the damage of old masonry by introducing stresses, retaining water or favouring harmful chemical reactions; the new mortars should not deprive the whole of its aesthetic characteristic.

New binders like cement or resins are used nowadays as mortars' constituents, but they are known to have low compatibility with old masonry, due, among other reasons, to their hygric behaviour (Teutónico et al. 1994; Veiga 2005; Moropoulou et al. 2005). Hence, alternative solutions must be found. Essentially, compatible mortars must have properties similar to the old materials that they are in contact with; thus their design implies a good knowledge of the original materials and this is a further reason for their characterization.

13.2 Mortar Sampling and Analysis

13.2.1 Sampling Procedure

Pozzolanic mortars were widely used in Portugal as rendering mortars in Roman times, as in the rest of the Roman Empire, especially linked to water bearing constructions, and in the form of *opus signinum* due to the lack of natural pozzolans in the mainland. Apart from the use of natural pozzolans in fortresses and punctual constructions with pozzolanic materials, documentation on the use of this material is scarce and is usually linked to commerce and characterization of pozzolans from the Azores islands (Casa Commercial Oliveira Machado 1867; Castanheira das Neves 1906). In this archipelago, pozzolanic materials are still extracted and used in construction, although lime/pozzolan mortars are being replaced by Portland cement mortars.

Table 13.1 Sample extraction: location, building type and dating

Location	Building types	Probable dating (centuries)
Tróia archaeological site	Fish salting tanks, baths	1st–4th
Conímbriga archaeological site	Baths, swimming pool, residential	1st–4th
Frielas archaeological site	Water channels, residential	3rd/4th
Alamo dam, Algarve	Dam	–
Machado de Castro Museum, Coimbra	Criptoportic under forum	16th
S. Brás Fortress	Fortress	16th/17th
Convent of Santa Cruz, Coimbra	Convent	17th
Safara, Alentejo	Church	19th, 20th
Ponta Delgada, Azores	Fortresses, residential, industrial	16th, 19th
Furnas, Azores	Residential	20th

Taking into account the known use of these materials throughout the ages in Portugal, samples of rendering mortars were taken from different locations, building types and periods (Table 13.1). Different periods are represented by Roman mortars from Conímbriga (Fig. 13.1), Tróia and Frielas, dating from the 1st to the 4th centuries A.D., samples from the 16th century obtained from Machado de Castro Museum, mortars from the 16th to the 17th centuries collected from S. Brás Fortress and Convent of Santa Cruz (Fig. 13.2) and 19th and 20th century mortars collected in the Azores, in Ponta Delgada and Furnas.

Sampling was performed in Roman archaeological sites, in tanks, baths and piping renders and on a dam; the constructions sampled were situated in central (Conímbriga) and southern Portugal (Frielas, Tróia, Algarve). Building types also included fortresses (Fortress of S. Brás, Pópulo Fortress), religious buildings (Main Church of Safara, Convent of Santa Cruz), industrial constructions such as a chicory factory and an iron smelting building (Fig. 13.4) and residential buildings in Ponta Delgada and Furnas in S. Miguel, Azores (Fig. 13.3).

Fig. 13.1 Conímbriga, 1st century A.D.

Fig. 13.2 Convent of Santa Cruz, Coimbra, 16th century A.D.

Locations were chosen taking into account diversity but mainly the known existence of this type of mortar. Therefore, for mortars from the 19th century onwards, sampling was performed on the island of S. Miguel, Azores. Samples from other ages were mainly collected in central and southern mainland Portugal and also from the Azores islands.

As sampling was often performed on archaeological sites, on monuments or buildings in a good state of conservation, severe restrictions to materials removal existed; hence the sampling did not follow a regular procedure. As a result, collected samples were often small and irregular. Although sampling at various heights, due to the effects of capillary water and rain as well as sampling on different walls due to their orientation was preferable, this methodology was not undertaken for the above mentioned reasons. Original mortars were extracted, ensuring the least damage possible and in certain cases, as in Conímbriga, conservation action was undertaken to prevent any possible damage due to the sampling.

Fig. 13.3 Building between nos. 29 and 37 of Rua das Águas Quentes, no. 31, Furnas, 20th century A.D., residential

Fig. 13.4 Iron smelting building, 19th century A.D., Ponta Delgada, industrial building

13.2.2 Analytical Methodology and Techniques

In order to obtain a complete characterization of the obtained samples, chemical and physical analysis techniques were performed, as well as microscopy. The adopted methodology was based on currently used processes (Biscontin et al. 2002; Silva 2003) and on the results obtained by different methods described by various authors (Alvarez et al. 1999; Callebaut et al. 1999; Ellis 1999; Goins 1999; Jedrzejewska 1960; Van Balen et al. 1999) and is shown in Fig. 13.5. This scheme was applied to all mortar samples, although capillary absorption and mechanical tests were not applied to mortars showing signs of disintegration.

Petrographic analysis is a major analysis tool that allows for the identification of mortar constituents and reaction products; but it is not always applicable, due to great desegregation of some samples and consequent difficulty in getting adequately thin sections, even after consolidation. Together with SEM/EDS, an initial but revealing characterization of the mortars is obtained; the use of XRD, XRF and TGA/TG confirms the mortar constituents in mineralogical and chemical terms and may be used to quantify mortar constituents. Acid dissolution, particle sieve analysis of the aggregate, determination of the mechanical strength and the degree of capillary absorption give further information on mortar constitution and properties. Inadequate sample quantity, especially when dealing with archaeological mortars, limits the possibility of carrying out all the necessary analysis techniques. In this unfortunately frequent case, tests requiring greater quantity, such as the determination of mechanical strength, capillary water absorption or petrography, may not be possible.

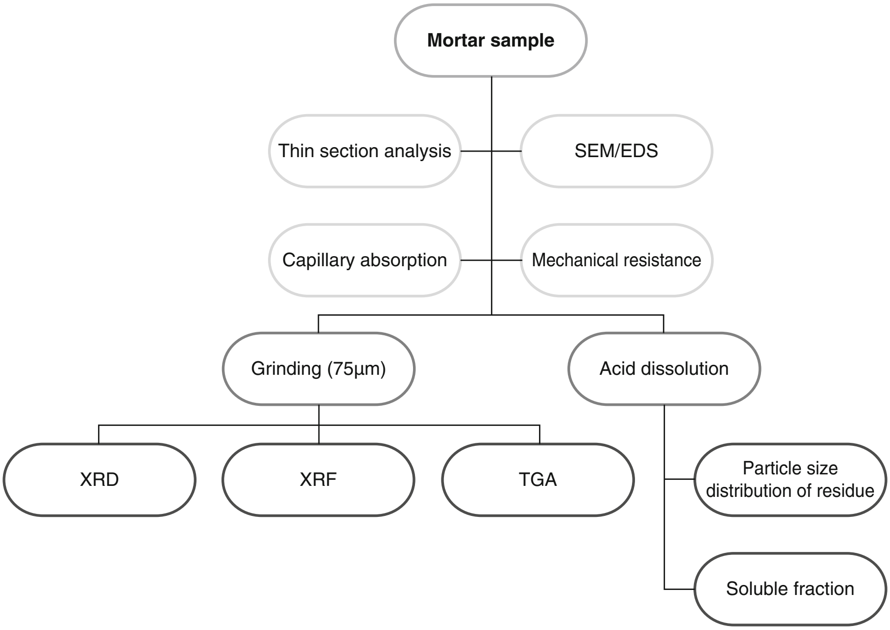

Fig. 13.5 Analysis methodology applied to mortar samples

13.2.2.1 Micro-morphology Analysis by Thin Section Observation

For visualization on the optical microscope, the preparation of thin sections was undertaken, involving cutting and polishing of samples and their encapsulation in epoxy resin prior to gluing on the section and shearing until a thickness of 30 µm was attained. In the case of disintegrated samples that could not survive the initial cutting, consolidation with epoxy resin was performed before cutting was undertaken.

The sections obtained were observed under the optical microscope in order to identify the constituents and possible interactions between them.

13.2.2.2 Scanning Electron Microscope (SEM) Visualization Coupled with EDS

This technique was applied to representative samples and allows detailed observation, with a resolution amounting to 200 Å; the consequent identification of compounds formed by the interaction between pozzolans and lime was possible, as well as that of the crystalline structure of the mortar's constituents (Pinto and Silva 2003). For this analysis a small freshly cut sub-sample is necessary, covered with a conducting material (usually carbon or gold) in order to achieve a better image resolution. The information from EDS (Electron Diffraction Spectrometry) complements the visual analysis, through chemical element characterization of an area or point under observation. For this analysis a Hitachi S-4100 (beam 0–30 kV; usually works at 25 kV) equipment was used with an EDS count time of 120 s.

13.2.2.3 Mechanical Resistance by Compressive Strength

Due to the great variability in samples extracted, compressive strength was determined by a method developed at LNEC (Magalhães and Veiga 2006; Valek and Veiga 2005) which consists in enclosing the mortar with a regular shaped mortar stronger than the mortar under analysis and of known facial dimension, to provide a known surface of force application. Usually a cement mortar with a 1:3 volumetric ratio and 40 × 40 mm surface dimension is used.

13.2.2.4 Water Absorption by Capillarity

Mortars sampled from ancient buildings often disintegrate when in contact with water. For this reason a specific testing procedure was developed at LNEC (Veiga 2005) involving the use of a metallic grid basket with a geo-textile, inside which the mortars are placed and weighed. Capillary absorption testing was performed by taking into account water intake and subsequent drying. The method avoids the immersion in water of friable samples but involves their constant contact with the saturated geo-textile and ensures that the loose particles are retained and therefore weighed with the sample.

13.2.2.5 Acid Dissolution

Acid dissolution was performed, based on ASTM-C 25–98 "Standard Test Methods for Chemical Analysis of Limestone, Quicklime and Hydrated Lime" in order to dissolve carbonates (calcite, magnesite and dolomite) and create a residue composed of the aggregate fraction. Acetic acid was used for *opus signinum* mortars in order to guarantee a residue composed of siliceous sand and crushed ceramics, as ceramic materials are not dissolved by this acid. In all other samples hydrochloric acid was used, producing a residue of siliceous sand. The residue obtained was dried until a constant mass was achieved.

13.2.2.6 Determination of Aggregate Particle Size Distribution by Sieve Analysis

Particle size distribution by dry sieving was performed on the residue obtained from acid dissolution. For *opus signinum* mortars, the dry residue was observed with a binocular magnifying glass in order to determine an approximate percentage of siliceous sand and crushed ceramic particles.

13.2.2.7 X-ray Diffraction (XRD)

By the use of this analysis technique, qualitative information on the crystalline compounds present in the samples is obtained, complementing the other analyses that were undertaken.

For this qualitative analysis, mortars were crushed and dried at a low temperature. The equipment used was a. Philips X'Pert PW 3040/60 using CuKα radiation, with operational conditions of 30 mA and 50 kV, automatic divergent notch graphite monocromator and speed registry 1°/2θ/min, with data acquisition by Philips X'Perta Data Collector v1.2. The difractograms were interpreted using the Joint Committee on Powder Diffraction Standards (JCPDS), namely quartz JCPDS 331161, K-feldspar (microcline) JCPDS 19932, plagioclase JCPDS 181202 and 20548, muscovite JCPDS 725, illite JCPDS 291496, kaolinite JCPDS 14164, calcite JCPDS 5586, dolomite JCPDS 36426, portlandite JCPDS 4733, magnesite JCPDS 8479, halite JCPDS 5-628, anhydrite JCPDS 6266, chabazite JCPDS 34137, heulandite JCPDS 24182, laumontite JCPDS 261047.

13.2.2.8 X-ray Fluorescence (XRF)

This technique allows the detection of elements present in the samples, by X-ray excitation of the sample (Silva 2003). Sample preparation was performed in accordance with the procedure used for XRD, followed by the use of powder pellets on which a Philips Fluorescence Spectrometer PW 1400 X-ray was used. When petrographic analysis cannot be undertaken, the quantities of the calcium oxide and silica give us an indication of the type of aggregate found in the mortar sample.

13.2.2.9 Thermogravimetric Analysis (DTA/TG)

Thermogravimetric analysis produces a continuous thermogram of the mass variation of a material with temperature rise, when it is heated at constant speed. In this register, variations due to chemical alterations in the materials such as dehydroxilation, oxidation, decarbonation or hydration can be observed. Each material has its typical curve permitting its detection through this technique (Hakateyama and Zhenhai 1998; Mackenzie 1957). This technique may be exceedingly useful for the detection of carbonate aggregate when thin section analysis may not be applied (Platret and Deloye 1994).

For this analysis a Netsch STA 409°C was used, and the temperature range was between 20°C and 1,100°C, with a heating rate of 10°C min^{-1}.

13.3 Characteristics of Pozzolanic Mortars

An analysis by acid attack, followed by XRF, XRD and DTA/TG permits a complete characterisation of mortar samples in chemical and mineral terms, allowing for the determination of aggregate and binder types and for the detection of reaction products such as calcium silicate hydrates. The use of SEM/EDS and thin section observation complements this analysis by confirming the composition and reaction products; and permits, additionally, the detection of changes in the mortars due to phenomena such as dissolution/precipitation or product transformation (into argillaceous materials, for instance) related to degradation processes.

13.3.1 General Composition

Acid dissolution enabled the determination of the soluble and insoluble fractions; however, this must not be understood as the division between aggregate and binder as acid attacks carbonates and may partially dissolve carbonate aggregates, yielding an error (Alvarez et al. 1999; Silva 2003; Van Balen et al. 1999).

Soluble fractions in mortars from Tróia were in the range of 28–37%; samples from Conímbriga revealed soluble content in the range of 20–30%; and mortars extracted from Frielas attained soluble fractions of 26–29%. With these results it can be inferred that *opus signinum* mortars have soluble fractions in the same range, with some dispersion in cases such as Tróia, where higher soluble fractions were sometimes attained. After the acid attack, insoluble residue was dried and *opus signinum* mortars revealed a mixture of crushed brick and siliceous sand and, in some samples from Tróia, of calcitic or dolomitic aggregate. This fact is a possible explanation for the higher soluble fractions obtained.

Other mortars of Roman origin such as those extracted at the Alamo dam or Machado de Castro Museum contained no crushed ceramic particles. In the latter case, soluble fractions were very low (10–18%) suggesting a high aggregate fraction or inclusion of insoluble pozzolanic material. Mortar from the dam produced a soluble fraction of 33%, similar to that of *opus signinum* mortars.

Samples taken from religious buildings differed considerably: whilst mortars from Safara church were brownish, possibly with some earth content, samples from Santa Cruz Convent, taken from interior walls, probably built for protection from damp, had a pink colouring due to the incorporation of brick powder. Soluble fractions were of 25% for Safara Church and of 30–37% in the case of Santa Cruz Convent.

Mortars extracted in the Azores island of S. Miguel can be divided into mortars from Ponta Delgada and mortars extracted at Furnas. In this last case, the soluble fraction was high, around 50% and the mortars may have some earth content. For mortars from Ponta Delgada, results showed a great variability and soluble fractions varied from 25 to 59%, although the range of 20–35% is characteristic of most of the analysed samples. Azores island mortars revealed an insoluble fraction composed of brown silt (probably natural pozzolan), basaltic aggregate or volcanic tuff and in a few cases, black volcanic sand.

In terms of the binder used in the studied mortars, a calcitic or dolomitic lime is the most probable material, determined no doubt by the availability of the original rock in the region. Analyses by XRD, XRF and DTA/TG were used to determine the type of binder and its accurate percentage in mortar composition.

13.3.2 Aggregate Types and Characteristics

As visualized after the insoluble residue was obtained, aggregates were composed by siliceous sand and crushed ceramic particles in *opus signinum* mortars. In some cases, such as Tróia and Machado de Castro Museum high contents of calcium and/or magnesium obtained by XRF confirmed the use of a calcitic/dolomitic aggregate. The only other case in which ceramic particles were used was in the mortars from Santa Cruz Convent, although in this case ceramics were finely ground.

Roman *opus signinum* mortars, especially those from Conímbriga showed some homogeneity in terms of aggregate (sand and crushed ceramic particles) size distribution (Fig. 13.6). It was possible, in this case, to determine the average particle size distribution of the ceramic particles by observation under a microscope. The similarity between these mortars led us to believe in a general practice for production of crushed ceramics, probably using the same type of materials and production process.

On the other hand, mortars from the Azores islands showed a great variability in terms of aggregate particle size distribution, not dependent on building type or time of construction. In this case, locally available aggregates such as basalt, volcanic tuff and black volcanic sand, were used. Images from SEM clearly showed volcanic aggregates of local origin that were incorporated in these mortars (Fig. 13.7).

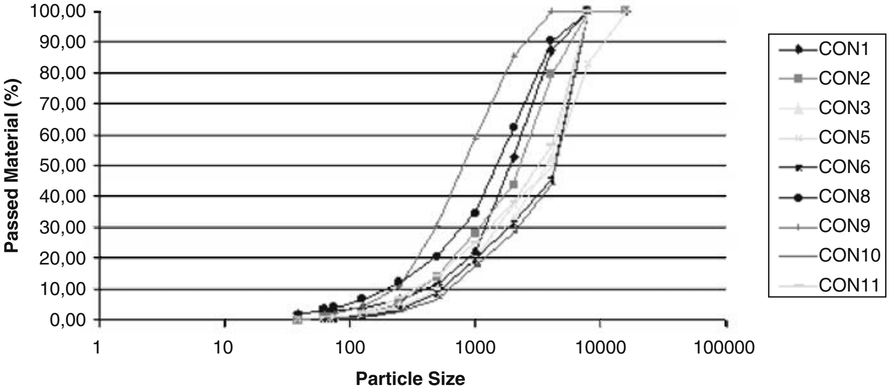

Fig. 13.6 Particle size distribution of Conimbriga samples

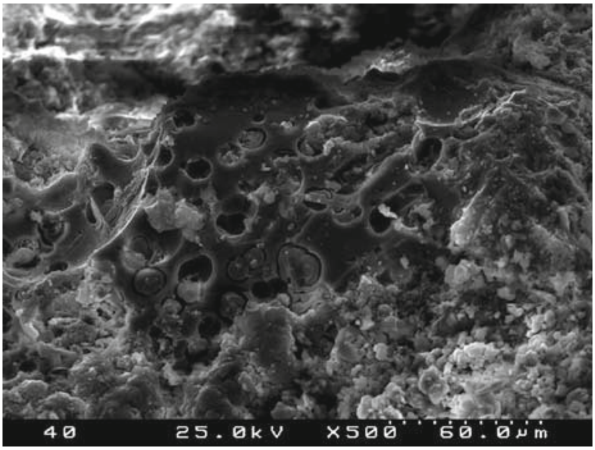

Fig. 13.7 Aggregate of volcanic origin in mortar from S. Miguel, Azores

13.3.3 Binders and Other Compounds Present in Mortar Composition

Analysis by XRF revealed high percentages of calcium in most mortar samples and in some cases (Tróia, Conímbriga, Ponta Delgada, Santa Cruz Convent and Machado de Castro Museum) magnesium content of approximately 5%. Although in cases in which this content is higher, usually a dolomitic aggregate is present (this is confirmed by lower siliceous content), the presence of magnesium may also indicate a dolomitic binder. XRD analysis confirmed the presence of calcite, dolomite and, in some cases, of magnesite. Lime contents are variable, but in Conímbriga, the content of CaO and MgO is mostly in the range of 17–23%, slightly lower than the soluble fraction. This can be clearly determined by DTA/TG curves through a mass loss corresponding to peaks produced at 960°C for calcite, 690–730°C for magnesite and a double peak at 730–790°C and 930–940°C for dolomite (Hakateyama and Zhenhai 1998; Mackenzie 1957). However, crystal size may significantly shift these peaks, especially in the case of calcite (Silva 2003). In Fig. 13.8, the peak produced at 700°C is due to calcite, probably linked to hydraulic compounds, resulting in a decarbonation at a lower temperature (Moropoulou et al. 1995). In mortars from the Azores islands calcite/magnesite content is only due to binder content as calcareous or dolomitic aggregate is unavailable on the island.

The presence of calcium silicate hydrates (CSH) is possible in many of the studied mortars documented by DTG peaks at temperatures 280, 480, 540, 550 and 580°C (Moropoulou et al. 1995). Some authors associate mass loss in the region of 200–600°C with the loss of hydration water from hydraulic compounds (Ingo et al. 2004; Moropoulou et al. 1998). However, between 200 and 650°C iron oxides and aluminous-silicates hydration water is freed (Moropoulou et al. 1995; Silva et al. 2005); therefore the mass loss in this range can also indicate the presence of argillaceous material or pozzolans. In this temperature range organic materials may also produce a mass decrease.

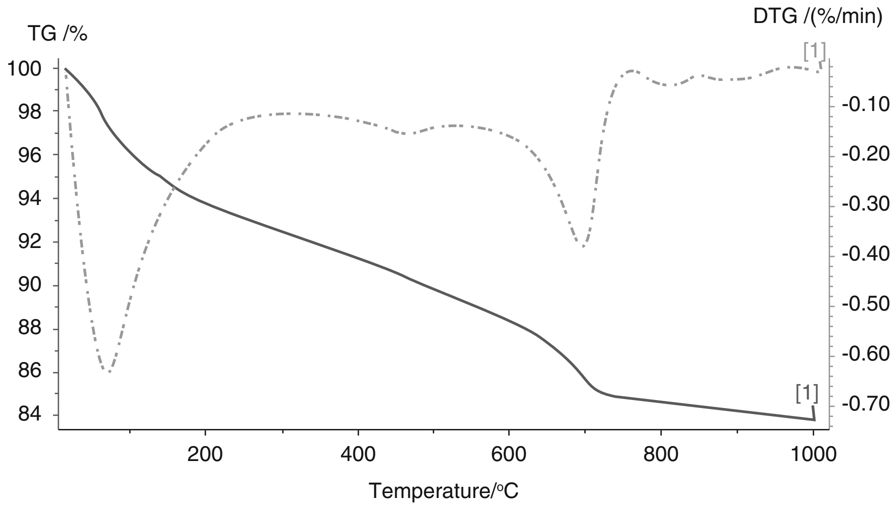

Fig. 13.8 Thermogravimetric analysis of sample from S. Brás Fortress in S. Miguel, Azores

In the case of mortars from the Azores island of S. Miguel, a peak appears in the DTG curve at 460°C (Fig. 13.8), that is due to the loss of hydration water either from CSH, from alumino-silicate phases or iron oxide contained in the mortar, due to pozzolanic additions.

Natural pozzolans are a common presence in mortars from the Azores, due to their wide availability. They may be detectable by their high content in feldspars and minerals such as pyroxenes, by XRD, and a high siliceous and aluminates content by XRF. Although they were probably used as an aggregate and are a part of the insoluble fraction, their action is also that of a binder; and products from pozzolanic reaction may be detected by XRD or, as mentioned above, by TGA. In the mortars studied, analysis by XRD detected zeolites, a possible reaction product, in samples from Tróia, Frielas, Santa Cruz Convent and Safara Church. Zeolites in themselves are only an indication of a possible pozzolanic reaction, as they may come from a natural source. In the case of *opus signinum* mortars, reaction rims on crushed brick particle borders indicate a pozzolanic reaction. These reaction rims were clearly observed by visual inspection (Fig. 13.9), especially in mortars from Conímbriga.

13.3.4 Ageing of Mortars

With time, mortars are subject to climatic action and to hydro-thermal changes as well as to the action of salts, either introduced by capillary water or contained in building materials. Furthermore, the action of water may induce dissolution and precipitation of compounds, creating changes in the mortars' microstructure. With time, mortar compounds not only react between themselves, but also with external inputs, from pollution to rain. This leads to internal changes that may benefit or induce the decay of the mortars.

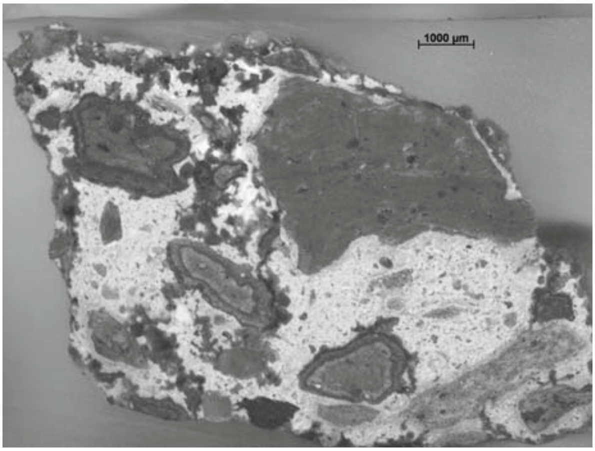

Fig. 13.9 Reaction rims on ceramic aggregate in *opus signinum* mortar

The action of salts was detected in many samples, most frequently by the presence of halite or gypsum/anhydrite. In Tróia, an industrial post for fish salting, halite was an expected presence, as was in Ponta Delgada mortars, as this is a seaside city. However, halite was additionally found in some samples from Conímbriga, which is situated in the interior. Gypsum/anhydrite was additionally detected in some Conímbriga mortars, but also in Tróia, Frielas, Santa Cruz Convent and Safara church. In archaeological sites these salts may have developed due to the groundwater action, as is also the case of Santa Cruz Convent. In Safara church, the presence of gypsum/anhydrite may be due to the action of pollution, resulting from reaction between sulphur dioxide present in the atmosphere or dissolved in rain, with carbonates.

In most mortars a phyllosilicate phase was detected composed of illite or kaolinite. This may be due to the use of earth in mortars or to decomposition processes of pozzolans and/or pozzolanic reaction products, leading to mortar decay.

In *opus signinum* mortars, which attained a great durability, thin section observation revealed that the action of water had dissolved and re-precipitated calcite inside the pores (Fig. 13.10), cracks and discontinuities between ceramic particles

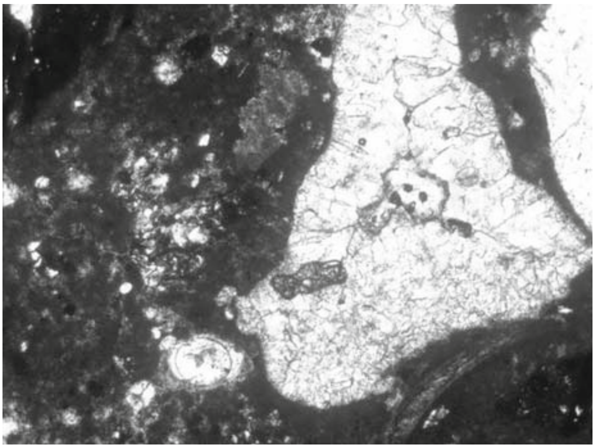

Fig. 13.10 Pore filled with calcite in *opus signinum* mortar from Conímbriga

and binder matrix, possibly where calcium silicate hydrates had previously formed (Velosa et al. 2007).

In Table 13.2, a general survey of the results produced by these analyses is presented, with the description of binder and aggregate composition, detection of traces of pozzolanic reaction occurrence and the presence of salts.

Table 13.2 General mortar composition

Location	Binder	Aggregate	Pozzolanic reaction products	Salts
Tróia archaeological site	Calcite/dolomite	Siliceous or calcitic/dolomitic sand crushed ceramic particles	Zeolites opal high mass loss in TGA between 200 and 600°C in some samples	Halite gypsum/anhydrite trona
Conímbriga archaeological site	Mainly calcite residually dolomite or magnesite	Siliceous sand Crushed ceramic particles	High mass loss in TGA between 200and 600°C in some samples	Halite anhydrite/gypsum
Frielas archaeological site	Calcite	Siliceous sand crushed ceramic particles	Zeolites high mass loss in TGA between 200 and 600°C in some samples	Seldom traces of anhydrite
Álamo Dam, Algarve	Calcite	Siliceous sand natural pozzolan	High mass loss in TGA between 200 and 600°C	No evidence
Machado de Castro Museum, Coimbra	Calcite/dolomite	Mainly siliceous sand calcitic/dolomitic sand	High mass loss in TGA between 200 and 600°C in some samples	No evidence
Convent of Santa Cruz, Coimbra	Calcite/dolomite	Siliceous sand finely ground ceramic powder	Zeolites high mass loss in TGA between 200 and 600°C in some samples	Gypsum
Safara, Alentejo	Calcite	Siliceous sand earth basalt(?)	Zeolites	Gypsum/anhydrite
Ponta Delgada, Azores	Mainly calcite seldom magnesite	Volcanic tuff basalt/trachyte natural pozzolan black volcanic sand	High mass loss in TGA between 200 and 600°C in some samples	Halite seldom traces of anhydrite
Furnas, Azores	Calcite	Volcanic tuff basalt/trachyte natural pozzolan	High mass loss in TGA between 200 and 600°C in some samples	No evidence

13.3.5 *Mechanical and Physical Characteristics*

13.3.5.1 Compressive Strength

In general, compressive strength tests on the extracted samples resulted in values from 2 to 4 MPa, except for mortars from the Azores, which registered lower values, from 1 to 2 MPa. Seldom values below 1 MPa or above 6 MPa were encountered, but there was a great disparity in the results. Compressive strength test results on mortars from Conímbriga are shown in Fig. 13.11.

In mortars from Tróia a negative impact on resistance was evidenced by a greater percentage of ceramic fragments in mortar composition. Inversely, in mortars containing dolomitic aggregate an increase in mechanical strength was felt.

The impact of binder percentage is also relevant—a higher binder content being related to higher resistance—and this was especially evident in mortars from S. Miguel.

13.3.5.2 Water Absorption by Capillary Action

Water absorption was generally low in the analysed samples, with capillary coefficients often being below 4 $kg\,m^{-2}\,h^{-1/2}$. The minimum value registered was 0.18 $kg\,m^{-2}\,h^{-1/2}$ from a Conímbriga sample, whilst the highest value was 18.71 $kg\,m^{-2}\,h^{-1/2}$ from a Ponta Delgada mortar which had a very low mechanical resistance, presenting evident degradation, as shown in Fig. 13.12, with capillary coefficients from mortars sampled in the Azores island of S. Miguel.

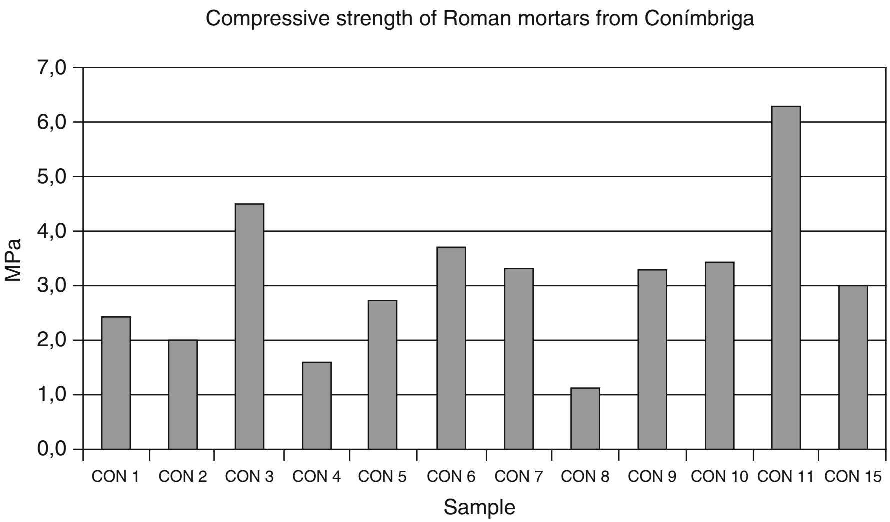

Fig. 13.11 Compressive strength of mortars from Conímbriga

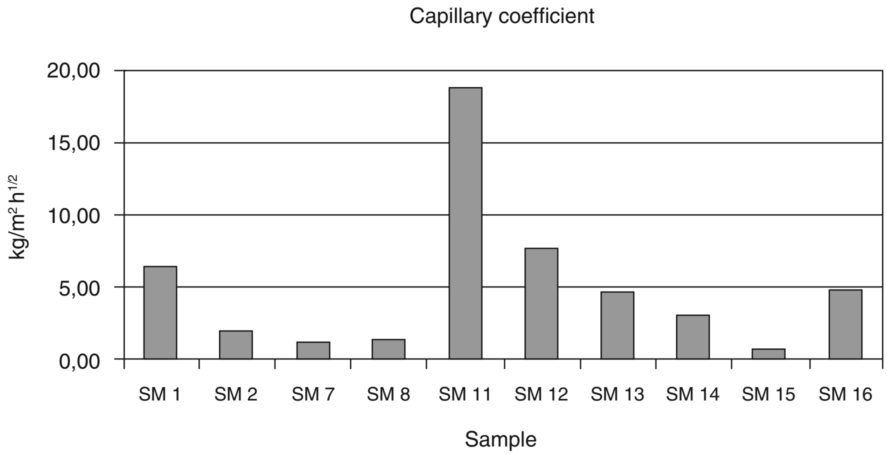

Fig. 13.12 Capillary absorption coefficient of mortars from S. Miguel, Azores

Maximum absorption in $kg\,m^{-2}$ was also measured and results followed the same pattern as capillary coefficients. Drying of mortars was registered, and usually the drying process was fast, although at a lower rate than absorption.

13.4 Design of Conservation Mortars

13.4.1 Compatibility with Substrates and Adjacent Mortars

Conservation practice often has to deal with the problem of mortar conservation, as mortar surfaces are extremely exposed and their deterioration severely affects the general appearance of buildings. Pathology manifestations in exterior mortars may have several causes such as the action of salts, water or the lack of cohesion. In many cases, renders suffer restricted damage and only need timely repair; in any case, compatibility of repair mortars with both the substrate and the pre-existing mortar is of major importance because incompatible mortars, besides having low durability and inadequate performance, may accelerate the decay of the pre-existing elements. In effect, strong, rigid mortars or mortars with high thermal deformability coefficients may induce significant stresses on the substrates and adjacent renders; materials with a low drying ability may contribute towards retention of water inside the thick porous masonry; binders with high content of soluble salts, such as cement and some hydraulic limes, may introduce those harmful salts into the masonry. Thus, the design of new mortars must take into account mechanical, physical, chemical and aesthetic compatibility in order to produce the least impact on the pre-existing construction, contributing effectively towards its conservation (Bonazza et al. 2005; Papayanni 2005; Veiga et al. 2001; Velosa 2006).

Total compatibility means having similar characteristics and the most direct method to attain it is to use new mortars with compositions close to the old ones. Another way is to study the old mortars' characteristics and to design new mortars with different components, verify if the main characteristics are similar and adjust the formula accordingly (Valek et al. 2000; Papayanni 1998; Moropoulou and Bakolas 1998). A mix of the two methods may give the best results: starting with a composition based on the same kind of binder and aggregates and performing trials and testing until the main characteristics are reproduced, concerning strength and elasticity, water behaviour and chemical behaviour, as well as aesthetics (Moropoulou et al. 1998; Papayanni et al. 2000; Veiga et al. 2001).

Archaeological sites are often prone to problems of mortar degradation as constructions were unearthed, suffering different degradation actions. In these cases, an exact knowledge of the mortar composition and characteristics is fundamental in order to produce similar mortars. These must be designed using similar raw materials and need to attain mechanical and physical characteristics in the same range as the mortars studied. Mortar properties must include drying facility in order to prevent the maintenance of water inside sustaining walls and a low cracking susceptibility, which indicates the capability of the rendering mortar to accommodate dimensional variations without cracking and without transmitting high stresses to the background (Veiga et al. 2006).

Although the same strategy must be followed in other specific buildings, such as monuments, in current practice a set of mortars with certain characteristics must be available for application in particular circumstances, for instance over adobe walls or irregular granite stone constructions.

Mortar design must also take into account its performance on the wall, either as a rendering or as a repointing mortar. In the latter case, higher mechanical strength, both in terms of compressive and flexural strength, must be attained. For rendering mortars, a special emphasis must be placed on their behaviour towards water, not only in terms of water intake, but also in terms of drying ability.

13.4.2 Materials and Proportions

Compatibility issues can be dealt with by using an adequate selection of materials and proportions in mortar composition. Most mortars from ancient buildings used air lime as a binder, composed mainly of calcite and/or dolomite and magnesite depending on the available natural resources. The use of Portland cement is inappropriate, due to the properties of mortars with this binder and its composition, with a high proportion of soluble salts that may damage adjacent construction materials. Other ancient mortar components such as aggregates and additives were also based on nearby resources. Common knowledge and financial capability were the final inputs towards mortar preparation and not all extracted mortars present good conservation conditions. Therefore, chosen materials and proportions for new conservation mortars must take this into account.

For specific applications, or due to their availability, pozzolans, either natural or artificial, were used. In these cases, the use of natural pozzolans is a definite possibility; however, these materials may also be used in other conservation actions, when final properties attained by lime/pozzolan mortars are compatible with substrates and existing mortars. The advantage of the use of pozzolanic materials is also linked to construction practice, as they may easily be applied in one layer and in humid conditions or under water.

Ancient mortars were proportioned in volume and usually in a ratio between lime putty and sand. Using powdered air lime, a volumetric proportion of 1:3 (binder:aggregate) usually provides good results as, for a well graded aggregate, this allows for a complete envelopment of aggregate by the binder. Pozzolans are usually considered as binders, but function both as binders and as aggregates, depending on their composition and the quantity used in mortars. For a few natural and artificial pozzolans, the volumetric ratio 1:1:4 (air lime : pozzolan : siliceous sand) has provided good results, compatible with irregular granite or calcareous walls (Velosa 2006).

13.4.3 Testing Procedures

Compatibility of new conservation mortars with substrates and adjacent mortars requires a complete set of testing procedures, namely:

- mechanical testing;
- cracking susceptibility;
- water intake—capillary action and wetting/drying;
- panels with in situ testing/adhesion.

Mechanical characteristics must be evaluated by flexural and compressive strength testing and the determination of the modulus of elasticity. Mortars must attain sufficient flexural and compressive strength, but values must not be exceedingly high (Table 13.3) as these are associated with resistant, inflexible mortars. In order to evaluate flexibility, the modulus of elasticity must be determined and values between 2 and 6 GPa are desirable for mortars to be applied over irregular calcareous stone (Table 13.3).

Cracking susceptibility is a testing procedure developed at LNEC (Veiga 2005) that measures the maximum force developed by a rendering mortar under restricted shrinkage conditions, the failure energy in strain testing (G) and coefficients CSAF (coefficient of resistance to the opening of the first crack) and CREF (coefficient of resistance to cracking evolution).

The behaviour towards water intake can be measured through capillary absorption testing and can be complemented by another test developed at LNEC designated as impermeable capacity test; this test allows for the measurement of the period of time that water takes to pass through a mortar layer before it reaches the substrate (W), the period in which water remains until drying (D) and wetting intensity (I). A

Table 13.3 Requisites for mechanical characteristics of conservation mortars (Veiga et al. 2001)

Mortar	Mechanical characteristics			Restricted shrinkage behaviour			
	Rt (MPa)	Rc (MPa)	E (GPa)	Fmax (N)	G (N mm)	CSAF	CREF
Limits exterior renders	0.2–0.7	0.4–2.5	2–5	< 70	> 40	> 1.5	> 0.7
Limits repointing mortars	0.4–0.8	0.6–3.0	3–6	< 70	> 40	> 1.5	> 0.7

clearer knowledge of mortar behaviour in terms of substrate protection and drying capability is attained by this test.

Value ranges of these characteristics for mortars tested at the age of 90 days are specified in Tables 13.3 and 13.4, considering compatibility with irregular calcareous masonry substrates.

Other tests, such as water vapour permeability, producing SD values (air thickness of equivalent diffusion), or artificial weathering complement the analysis of new mortars intended for conservation practice. Results related to testing on ancient mortars are not directly comparable to these values, obtained with new mortars aged 90 days, as it is known that mechanical strength of lime mortars improves with time due to carbonation and that there are changes in the porous structure of this material. However, these indicative values are based on experimental results and most of the analysed samples of ancient mortars achieved mechanical strength values inside or, comprehensibly, above this indicative range. In terms of capillary absorption, values obtained from ancient mortars have a higher variability due to degradation mechanisms or calcite deposition (Velosa et al. 2007), interfering with the pore structure. The values indicated in Table 13.4. are intermediate and may be re-evaluated for specific cases, with absorption characteristics outside this range.

In order to produce the best results, the execution and testing of panels on the construction itself is recommended, comprising adhesion testing, among other tests. It is important that this testing procedure is performed on the adequate substrate and with the same execution technique as is to be applied, in order to provide adequate results. These in situ applications also permit the evaluation of adequate execution conditions, considering additional factors, such as substrate influence, weather conditions and environmental pollution.

Table 13.4 Requisites for water and climate behaviour of conservation mortars (Veiga et al. 2001)

Mortar	Water behaviour					Artificial weathering
	Classic tests		Impermeable capacity			
	SD (m)	C ($kg/m^2 h^{1/2}$)	W (h)	D (h)	I (mv h)	
Limits exterior renders	< 0.08	< 12; > 8	> 0.1	< 120	< 16,000	Medium
Limits repointing mortars	< 0.10	< 12; > 8	> 0.1	< 120	< 16,000	Medium

13.5 Conclusions

This paper presents a possible characterization scheme for lime/pozzolan mortars that was used successfully for rendering mortars from various ages and locations in mainland and insular Portugal. Nevertheless, this scheme may be improved by other analysis techniques: petrographic analysis may be applied initially in order to characterize mortar components, but consolidation techniques of samples must be improved in order to achieve a successful turnout; evaluation of the elastic modulus and water vapour permeability have been initiated on ancient mortars and these testing procedures will be incorporated in the analysis sequence; the execution of XRD on the fine fraction of mortars, without the interference of the aggregate, is another possibility that will give more precise information on binder composition. However, it is not always possible to withdraw samples in sufficient quantity to execute all these analyses and smaller testing schemes that will allow for the knowledge of components and approximate quantitative composition must be used.

The results obtained from characterization yielded information on the raw materials used for mortar composition; air lime, although sometimes dolomitic, was the common binder; siliceous sand, together with natural pozzolans and crushed ceramics were also incorporated into most mortars. Traces of pozzolanic reaction were harder to detect but reaction rims were visible under the optical microscope and DTA/TG results gave clear indications of the presence of products formed by this reaction. Carrying out XRD on the fine fraction of the mortar may be a valuable aid for the detection of pozzolanic reaction compounds. An interesting outcome from this set of analysis techniques on ancient mortars was awareness of the changes taking place over time, either by degradation or by re-precipitation of calcite, leading undoubtedly to variations in physical and mechanical characteristics. This is an important factor for the design of conservation mortars and indicative values for their characteristics at the age of 90 days are a first approach towards adequate formulation of conservation mortars, taking into account that these characteristics and those of adjacent rendering mortars will evolve with time. With these indicative values, together with the use of adequate materials, there is a greater possibility of achieving compatible mortars. However, these values are constantly being re-evaluated and similar experiments should be performed at other locations with a tradition of different materials and/or construction techniques, as it is quite evident from the results indicated in this paper that there is a great variability associated with ancient mortar characteristics. Nevertheless, compatibility of conservation mortars is the desired achievement and, according to the analysis scheme described, mortars with compatible characteristics were successfully developed for various specific cases, such as the archaeological site of Conímbriga.

To preserve the ancient structures the design of repair mortars must be based on compatibility criteria. Compositions similar to original mortars assure good performance and durability, hence in a number of situations, namely in Roman archaeological sites, lime and pozzolan mortars with studied proportions are good solutions. Even when original mortars do not contain pozzolanic materials, lime and pozzolan mortars are possible adequate solutions, as they have characteristics compatible with most substrates and they are durable, water resistant materials.

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Chapter 14
Roman Cements: Key Materials of the Built Heritage of the 19th Century

Roman Kozłowski, David Hughes and Johannes Weber

14.1 Introduction

Highly hydraulic binders, known as natural or Roman cements, were key materials for the economic and easy manufacture of stuccoes for the exterior of buildings during the 19th and early 20th centuries. Roman cements were produced by burning naturally occurring deposits of calcium carbonate rich in clay minerals. They were distinguished from other hydraulic binders principally by a very short setting time, agreeable texture and colour, little shrinkage on setting and excellent weather-resistance. They were first produced in England in 1796 when James Parker patented a cement known as Parker's or Roman cement (Parker 1796). The material was obtained by firing clay-bearing calcareous nodules found in the London clay beds on the Isle of Sheppey, England. Despite implied links to the Roman binders, Parker's 'Roman cement' was a true hydraulic cement very different from the hydraulic binders used by the Romans in which pozzolanic materials, not cementitious in themselves, had combined with lime in the presence of water to form insoluble compounds possessing cementing properties. The Roman cement mortars were mainly used in construction where masonry was subjected to moisture and high levels of strength and durability were needed.

The manufacturing of Roman cement developed in mainland Europe after 1850. In contrast to England, where cements were largely produced from the nodules, marls were the usual source. Despite this difference, the term 'Roman cement' and its translation into various national languages was widely used to describe natural cements from both sources.

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Roman cement mortars were highly recommended in contemporary technical literature and textbooks for stuccoists as being ideal for plastering applications (particularly run mouldings and castings) (Fig. 14.1). They were used on a massive scale for economic and easy manufacture of ornaments and renders for the exterior of buildings in the period of European Historicism and Art Nouveau (19th/early 20th century). Roman cement is now often referred to as the exterior equivalent of gypsum plaster as it offered the same speed of set and manipulation as gypsum yet could withstand exterior conditions very effectively. The unique properties of this particular binder and the specialized methods of its usage enabled craftsmen to develop a stylistic language of architectural decoration which today determines the aesthetic appearance of central areas in most European cities.

In the UK, the use of Roman cements gradually declined in the latter half of the 19th century, being displaced by the newer Portland cement which came to dominate the market. In contrast, it is known from contemporary sources that—e.g., in the Austro-Hungarian Empire of 1887—the amount of Roman cement produced was five times higher than that of either Portland cement or hydraulic lime (Tarnawski 1887). In the years following World War I, the dominance of the newer Portland cement on the market and modern functional architecture, with its total absence of ornament, brought a quick decline in the production and use of Roman cements.

The lack of appropriate binding materials—matching those available to the craftsmen of the 19th century—has for a long time deprived architects and conservators of the original historic technology for the repair and conservation of such objects. A further problem was an absence of any broader information on the material characteristics, ageing behaviour and adequate technologies for protection and

Fig. 14.1 Former warehouse of the Court Theatres, 1873, by Gottfried Semper and Carl Hasenauer, Lehargasse 6–8, Vienna. An exquisite facade combining brick, stone and Roman cement renders preserved in the authentic, naturally aged state

restoration, which resulted in little understanding for the necessity for well-designed, high-quality interventions. Although there exists a range of historic literature and archival sources describing raw materials, manufacturing process, composition of mortars as well as application and craft techniques (e.g., Vicat 1828, 1837; Pasley 1830; Austrian Standard 1878; Tarnawski 1887; Schoch 1896; Eckel 1905; Bohnagen 1914), the quality of this literature is inconsistent due to the changing regional markets and scientific approach and methodology during the period in question i.e., late 18th to early 20th centuries.

Only relatively recently, with growing interest in European art of the late 19th/ early 20th centuries, have attempts been undertaken to investigate these historic renders and to develop strategies and adequate measures for their conservation. The RENDEC project (1997–1999) provided ample information on historic cements and mortars used in Central Europe in the period around 1900 (Decorated Renders 1999). Cailleux et al. (2006) evaluated properties, microstructure and deterioration mechanisms of historic concretes produced with the use of natural cements from the French Rhône-Alpes region. The French natural cement Prompt is still produced by Vicat by burning marl deposits at Chartrouse in the Rhône Alps at moderate temperatures and is the only natural cement produced in Europe. Pecconi et al. (2005) provided information on petrographical, mineralogical and chemical characteristics of the ‘artificial stones’ used to decorate palaces in Florence in the 19th and 20th centuries. All materials investigated were hydraulic mortars and the use of natural cements to produce the decorations can be inferred from the presence of unhydrated di-calcium silicate (belite) identified in some samples. Varas et al. (2005) characterised hydraulic mortars manufactured with the use of Spanish natural cements at the end of the 19th century. The ROCEM project, supported by the European Commission as part of its 5th Framework Programme, has extensively investigated historic renders based on Roman cements and has re-established this historic material and technology to the conservation practice (Weber et al. 2007; Hughes et al. 2007a–c, 2008, 2009; Tislova et al. 2008; Vyskocilova et al 2007). The aim of the present publication is to provide information on Roman cements, awaken interest in this unique material and technology and help conservation authorities and practitioners to plan and carry out restoration of historic Roman cement stuccoes to new high standards.

14.2 What is Roman Cement?

Roman cements were produced from marls—limestones containing clay—frequently sourced in the form of cement-stones embedded in clay or shale deposits. This natural combination of calcareous and argillaceous matter required only moderate calcination(800–1200°C)—below the sintering temperature—and subsequent grinding to produce a binder of remarkable strength and durability. The success of the cement synthesis at low temperatures resulted from the natural intimate mixture of lime and clay (source of silica, alumina and iron oxide) in the marl, which could not be attained in any man-made mixture.

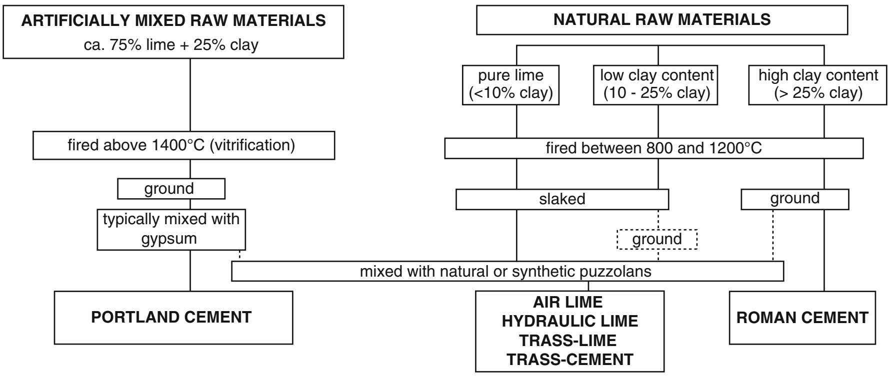

Fig. 14.2 The 'family tree' of historic binders

Roman cements can be placed between hydraulic limes and Portland cements in the sequence of binders shown in Fig. 14.2. They differ from hydraulic limes in that they are not high in free lime and therefore require grinding rather than slaking. They differ from the Portland cements by the different chemistry resulting from considerably lower calcination temperatures. While C_2S (dicalcium silicate, belite) is the major hydraulic phase in Roman cements, C_3S (tricalcium silicate, alite) is the major phase in ordinary Portland cement.

The Austrian Standard of 1878, modified in 1890, provides a contemporary definition of Roman cements: 'Roman cements are products obtained from argillaceous marlstones by burning below the sintering temperature. They do not slake in contact with water and must therefore be ground to a floury fineness.' It specifies the range of setting times which facilitated the choice of a suitable material for a given decorative task: 'Roman cements bind fast, medium and slow. By fast binding cements one should understand those which with no addition of sand start to harden within 7 min from the moment water is added. Roman cement is considered a slow binding variety if hardening starts later than after 15 min'. Other features specified by the standards are: volume consistency under water and in air, fineness of grinding, as well as tensile and compressive strengths for various cements and ages, as given in Table 14.1.

Table 14.1 Strength specifications for Roman and Portland cement mortars as given by the Austrian standards of 1878 and 1890

Age	Tensile strength (MPa)			Compressive strength (MPa)		
	Roman cement		Portland cement	Roman cement		Portland cement
	Quick ≤ 15 min	Slow > 15 min		Quick ≤ 15 min	Slow > 15 min	
7 days	≥ 0.4	≥ 0.5	≥ 1			
28 days	≥ 0.8	≥ 1	≥ 1.5	≥ 6	≥ 8	≥ 15

14.3 Raw Materials and the Production of Roman Cements

Suitable marlstones, which were exploited for Roman cements, could be found in different geologic formations: the best known English Roman cements were made by calcining Septarian nodules from the Eocene London clays or from the Jurassic and Cretaceous formations along the coastlines. In continental Europe, deposits of stratified marls were mined in France, especially in the Jurassic areas of Burgundy and the Cretaceous region near Grenoble. The marls quarried in the Eastern Alps were of Jurassic, Cretaceous or Eocene age, such as in the Bergamo area in northern Italy, in Tyrol, the area near Salzburg and in the area west and south of Vienna. Other important sites of production were situated mainly in the Swiss Pre-alps, in Southern Germany, Bohemia and Galicia, today's Southern Poland.

The marlstone was crushed to small, fist sized fragments and mostly fired in shaft kilns—an early example is shown in Fig. 14.3. The exact type and size of those kilns varied, but with growing industrialisation during the 19th century an increasing number of big factories were running batteries of kilns for the production of Roman cement. The usual fuel was coal, coke, wood or turf. The calcination temperatures had to be high enough to largely enable the decomposition of calcite, but

Fig. 14.3 Production began in this shaft kiln in 1811 which is located in Sandsend, near Whitby, England. The shed at the rear is where barrels used for transportation were manufactured

on the other hand low enough to prevent sintering. Under such conditions, different degrees of calcination were likely to occur even within one batch.

Unable to slake in contact with water, caused by its lack of free lime, the calcined material, the Roman cement 'clinker', had to be ground to a fine powder. Then it was packed usually into 250 kg barrels or 60 kg sacks and shipped by rail or river.

14.4 Historic Roman Cement Mortars

During the ROCEM project, a number of historic buildings across Europe, rendered and decorated with Roman cement mortars, were investigated (Weber et al. 2007). They covered a long period of the 19th and early 20th centuries. The samples of mortars collected were representative of different modes of application, from cast ornaments to in-situ applied renders and hand-run elements. The most evident observation was the generally excellent state of preservation of the investigated elements.

14.4.1 Aggregate

A striking observation was a wide range of aggregate content: for cast and hand-run mortars the aggregate contents were low—typically 20–25 vol.%, for renders and especially pointing mortars the proportion was higher—generally 40–50 vol.%. The results match the recipes for mortar mixtures given in the handbooks of the 19th century. A wide range of mineralogical materials were used as aggregate, which reflected local geological conditions.

14.4.2 Hydrated Binder

The microstructure of the Roman cement pastes shows a very fine 'groundmass' encapsulating a significant amount of unhydrated remnants of original cements (Fig. 14.4); in some cast mortars their amount can even outmatch the inert aggregate. Incompletely hydrated grains of C_2S—a principal compound of Roman cements—are most frequent, as well as gehlenite (C_2AS), rankinite (C_3S_2), wollastonite (CS) and a number of solid solutions in the system SiO_2–CaO–Al_2O_3–Fe_2O_3. A thorough investigation by means of SEM/EDX permitted the classification of the unhydrated cement grains into three major groups: overfired, well fired and underfired. The different degree of calcination within the same batch of the raw material was the result of its natural inhomogeneity as well as temperature gradients within a kiln. The remnants are of significant importance for the mortar properties, as they act as aggregates strongly bound to the surrounding hydrated matrix of

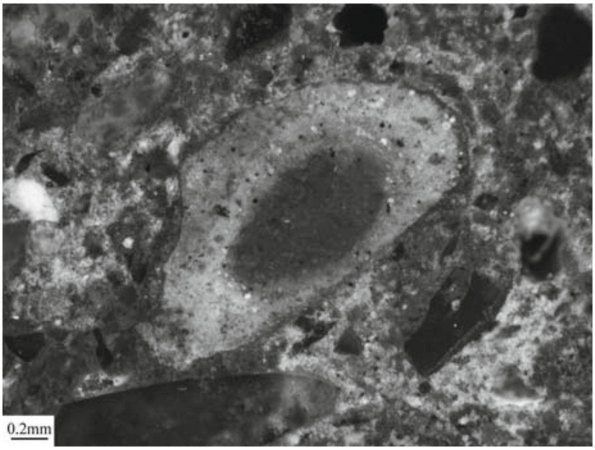

Fig. 14.4 A remnant of the original Roman cement showing a hydrated ring around an unhydrated core

the cement. Their maximum grain size is around 1 mm, an indication that historic Roman cements were ground quite coarsely. The historic Roman cements mortars are usually strongly carbonated.

14.4.3 Layer Structure

The plain renders varied in thickness between 2–50 mm. As a result of the low shrinkage on setting, it was possible to apply Roman cement mortars much thicker in comparison to lime coats which did not exceed 10–12 mm. The renders could consist of a single render coat applied directly to a solid masonry background or be a sandwich structure in which the render coat was followed by the second coat providing a final level surface. Also, run mouldings and castings usually had finer outer layers and a coarse interior core (Fig. 14.5).

There is well documented evidence that early English Roman cement stuccoes were coloured by limewashes and later by oil paints, sometimes to imitate the colour of Bath stone. The post-1850 Roman cement stuccoes in Central Europe were usually unpainted, and Roman cement wash, composed of the cement diluted in water, was a universal technique for finishing them.

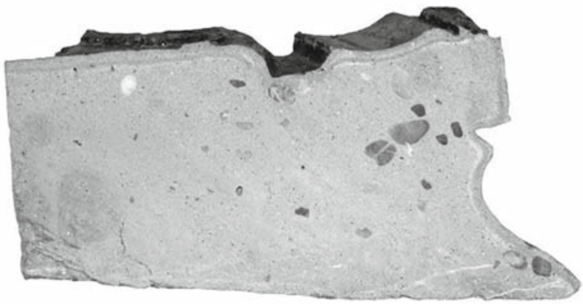

Fig. 14.5 Cross-section of a typical Roman cement cast element with a very low amount of aggregate including some coarse-grain gravel; the surface zone is coloured by residues of glue or oil coming from a mould or an isolating medium

Table 14.2 Compilation of physical and mechanical values assessed for historic Roman cement mortars

Historic Roman cement stuccoes	Compression strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Bulk density ($g.cm^{-3}$)	Water-accessible porosity (vol.%)	Water absorption coefficient ($kg\,m^{-2}h^{-1/2}$)	Water vapour permeability 10^{-10} ($kg\,m^{-2}sPa$)
Render (with lime)	11	0.6	5.4	1.43	39	23	11
Render (pure RC)	38 ± 19	1.6 ± 0.8	21 ± 10	1.7 ± 0.04	28 ± 9	9 ± 4	4
Casting	44 ± 7	2.1 ± 1.5	17 ± 1	1.64 ± 0.02	31 ± 1	7 ± 0.5	3

N.B. the compressive strengths were established from samples prepared to a size of 40 × 40 × 20 mm and the values should be appropriately factored in order to yield comparisons with values obtained from conventional cylinders or cubes

14.4.4 Porosity

A distinctive feature of most historic Roman cement mortars is their high porosity accessible to water (30–40 vol.%), combined with generally high mechanical strength and excellent durability. Mercury porosimetry has revealed two principal categories of pores. The finest pores with the pore diameter below 0.2 μm are present within very well-hydrated mature Roman cement matrix. Larger pores with the diameters of around 1 μm are characteristic of mortars strongly exposed to air in which the hydration process was interrupted by the evaporation of water.

14.4.5 Physico-Mechanical Parameters

Historic Roman cement mortars show high strengths and moduli of elasticity, but at the same time they are highly porous and accessible to water. They can thus be regarded as strong, brittle and porous materials. The addition of lime, quite common for renders but never for architectural castings, significantly decreases the strength at increased elasticity, porosity, water absorption and vapour permeability (see Table 14.2).

14.5 Conservation Problems

Roman cement stuccoes are generally very durable. Fine surface cracks, forming an irregular network not related to building features, are a distinct characteristic of all Roman cement renders and architectural castings (Fig. 14.6). They are caused by normal drying shrinkage and usually do not lead to damage. Only rarely can they

Fig. 14.6 Typical irregular network of fine shrinkage cracks characteristic of Roman cement renders

widen if the stucco is exposed to the severe impact of rain water, especially at the top of buildings. Very exposed Roman cement surfaces can suffer from erosion of their close compact structure. Wider cracks with displacements can also appear as the result of structural movements which cannot be accommodated by rather hard and stiff Roman cement stucco. Hollow sounding areas, indicative of a loss of bond, are common but lead, exceptionally, to losses only when water is freely admitted and trapped between the stucco and the wall.

An improper maintenance, making the stuccoes vulnerable to chronic excessive dampness, is a far more frequent cause of failure. In the upper parts of the facades the source of dampness can be damaged or ineffective exterior drainage systems leading to rain water leaks. In the area at ground-level, ineffective drainage and waterproofing of the foundation walls can lead to the intrusion of moisture and destruction of the renders of the façade, mainly due to transmission and crystallization of salts.

The main conservation problem, however, is the later repair and renovation measures irreversibly altering the original surfaces. Few materials have been so little appreciated and treated as Roman cement stuccoes. Years of neglect, the accumulations of paint layers or sprayed cement coatings, damaging cleaning and patchy repairs with improper materials adversely affect and aesthetically degrade a substantial part of the 19th and early 20th century built heritage (Fig. 14.7). Original renders and decorative castings are often removed when in poor condition rather then conserved or replaced. Once removed or irreversibly coated, the important information on past aesthetic concepts, technology and building

Fig. 14.7 A Roman cement casting disfigured by a thick coating of a cement spray, removed mechanically from a part of the element

skills is lost for good. Therefore, the unaltered Roman cement facades, preserving their original colour and architectural surface in an undisturbed state, are rare in spite of the fact that the technique was used on a massive scale during the period of rapid urban growth in Europe. Efforts must be maintained to understand, respect and sustain this relatively modern architecture by a careful evaluation and conservation.

14.6 Calcination of Roman Cements

14.6.1 History

It is generally agreed that the calcination of marls to produce Roman cements should be conducted at 'low' temperatures and that over-burning produces an inferior product (e.g., Eckel 1905). However, even Eckel, in his definitive English language text, suggests that this may be between 900–1200°C. Historic texts frequently refer to the observation that the best cements often contained a small amount of calcite which had not been de-carbonated during the firing process. The period of calcination has been variously reported as lying between 30–72 h but this would include the heating, soaking and cooling cycles. Pasley (1830) suggested a period of 2–3 h at red heat would be sufficient.

14.6.2 Cement Formation on Heating

Calcination of various marls in a laboratory kiln has revealed the important reactions which take place during production: the decomposition of calcite to lime, the dehydration and decomposition of clay minerals to amorphous aluminosilicates and the reaction of lime with quartz and clay mineral decomposition products to give dicalcium silicate—belite as a mixture of two structural modifications α' and β and, at higher temperatures, calcium aluminosilicate—gehlenite (Fig. 14.8). As the calcination is increased, the calcite, quartz and amorphous contents decrease; the free lime increases to a maximum before decreasing; the gehlenite increases; the total belites increase but with α'-belite dominating at low temperatures before transforming to β-belite with an increase in temperature (Hughes et al. 2007, 2008, 2009). The cements are therefore very sensitive to calcination temperature and yield best strengths at relatively low temperatures. The optimum cements are associated with the maximum α'-belite content, a high amorphous phase together with a residual calcite content

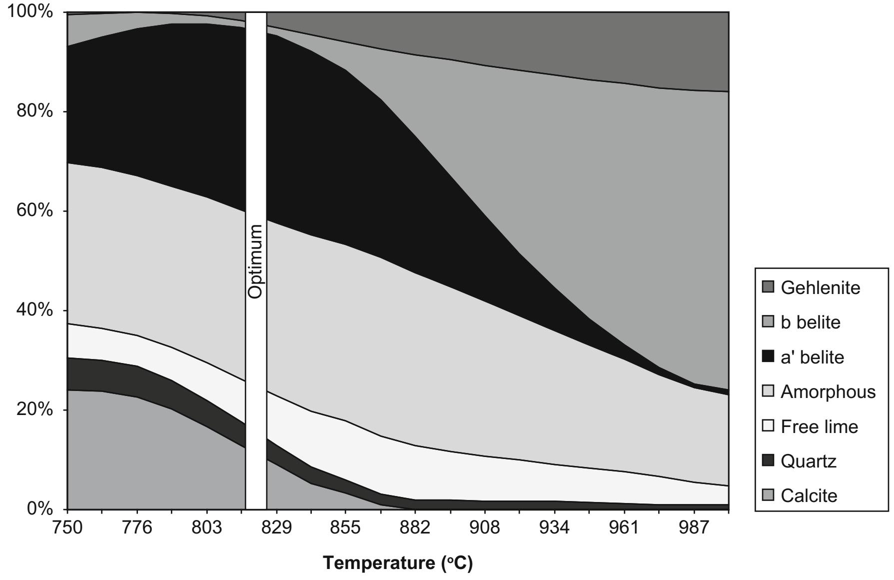

Fig. 14.8 Change of composition of a Roman cement with temperature—the main components of the optimum material are α'—belite, amorphous phase and smaller amount of undecomposed calcite

indicating incomplete calcination. It is clear that the historic descriptions of quality cements have been confirmed by present-day investigations: the best cements do indeed retain a proportion of calcite and over-burning yields inferior cements.

14.7 Hydration, Strength Development, Porosity

Typical water/cement ratios used in mortar and paste formulations are in the range of 0.65–1.0. The hydration and strength development of Roman cement proceed according to a two-step mechanism:

Step 1—Roman cement pastes harden within a few minutes after the rapid initial set. Six hours strength values of up to 4 MPa are obtained. Early strength development was found to correlate with the formation of crystalline calcium aluminum oxide carbonate (or carbonate hydroxide) hydrates (C-A-H) (Vyskocilova et al. 2007). The workable time may be considerably extended by admixing small amounts of appropriate retarders like citric acid and potassium citrate (Hughes et al. 2009).

Step 2—After a varying dormant period, depending on the type of Roman cement, further strength development leads to high final strength values—after 1 year compressive strengths exceeding 20 MPa (Fig. 14.9) were measured using

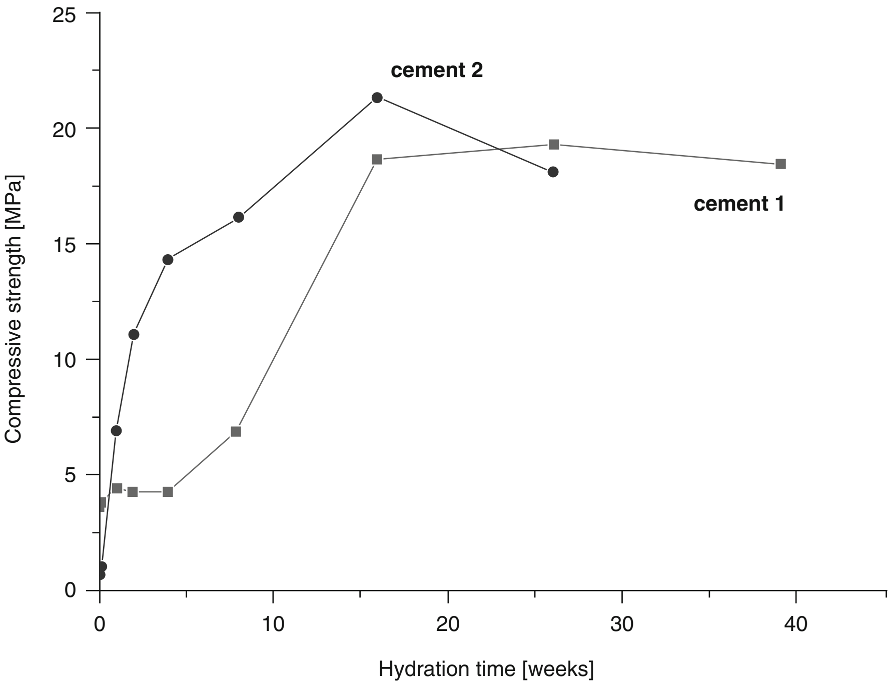

Fig. 14.9 Typical strength development assessed for two types of Roman cements (cement 1—no dormant period, cement 2—high early strength, extended dormant period)

small cylinders of cement paste, height : diameter ratio 1:1. Further strength development proceeded due to the hydration of belite, α’-belite being more reactive than β-belite, yielding calcium silicate hydrates—the C-S-H gel. Late strength development continues over several years and may lead to high final strength values: in 100 year old historic Roman cement mortars, compressive strength values up to 50 MPa were measured (see Note on Table 14.2).

The pastes of the rapid-hardening Roman cements showed a characteristic development of the pore structure with the time of hydration (Tislova et al. 2009; Vyskocilova et al. 2007). Mercury intrusion porosimetry revealed generally a unimodal distribution of pore sizes. However, the ‘threshold’ pore width, corresponding to the minimum pore dimension of the porous structure, decreases considerably with increasing curing time (Fig. 14.10). At early ages, a relatively open pore structure is produced by the quick growth of the C-A-H phases in the pastes with the threshold pore diameter between 0.2 and 0.8 μm. The initial open structure remains unchanged during the dormant period of the paste which can extend up to several weeks. Only then does the threshold pore width shift to smaller values concentrated around 0.02 μm, which is the result of filling larger pores by the formation of the C-S-H gel.

The evolution of the pore structure correlates well with the development of the specific surface area which is determined by water vapour adsorption. In the case

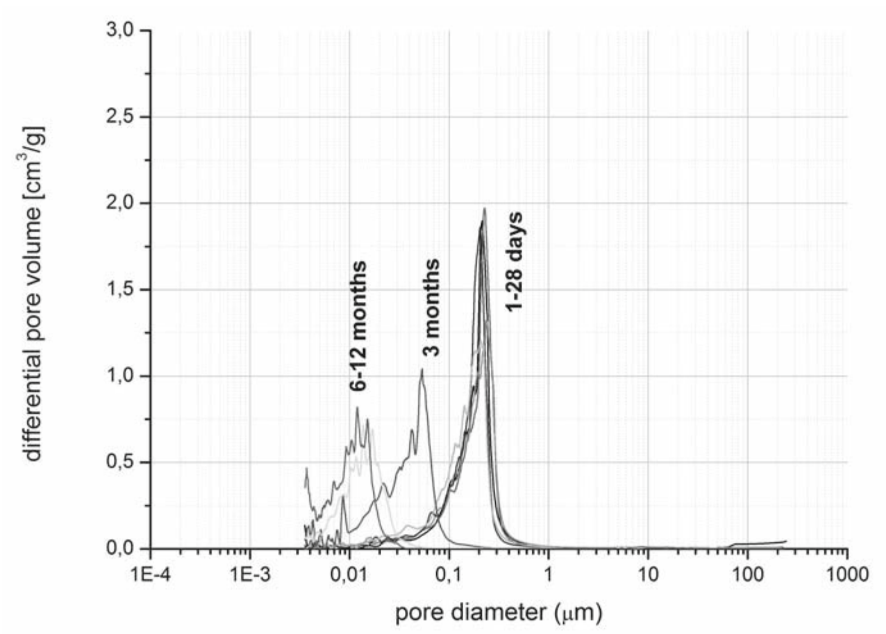

Fig. 14.10 Evolution of the pore-structure of a Roman cement paste during hydration: the initial open structure remains unchanged during the dormant period after which the threshold pore width shifts to smaller values due to filling of pores by the formation of the C-S-H gel

of the Roman cements, the surface area of the early structure produced by the quick growth of the C-A-H phases does not exceed approximately 20 $m^2 g^{-1}$. Formation of the C-S-H gel brings about an increase of the surface area up to 120 $m^2 g^{-1}$, the value being approximately proportional to the amount of the C-S-H gel formed.

14.8 Restoration of Roman Cement—Roman Cement for Restoration

14.8.1 Casting Architectural Decorative Details

Historically, Roman cements were widely used for the mass-production of cast decorative elements in large numbers and at reasonable costs. Roman cement mortars had the advantage of being more durable in outdoor exposures than gypsum stuccos and far less expensive than terracotta or zinc plate.

Originally, the castings were produced in elastic moulds made of animal glue; despite the use of oil as an isolating medium, they were very sensitive to the prolonged action of moisture. The typically rapid setting of Roman cement mortars allowed for a quick removal of the casts and enabled therefore the repeated use of the moulds. In order to reduce their weight the casts were normally hollow and were fixed to the masonry on wrought iron nails. By their typically pinky-brown to dark brown colour, Roman cements resembled burnt clay, and this is probably why cast Roman cement elements were frequently left unpainted, though the decorative elements could be integrated into a more elaborated colour concept of the façade by painting them.

In accordance with examinations of historic Roman cement mortars, the cement to aggregate ratio should be at least 2:1 by volume, for example 3:1 is perfectly acceptable. So the mixture must be much richer in cement than mortars for rendering. The aggregate can be quite coarse, with the maximum grain size reaching even 1 cm; but well rounded gravel should be preferred to ensure good flowing properties. A good consistency is obtained with a water to cement ratio of 0.65 at which exact copies, free of voids, can be produced even for casts rich in fine details.

Due to the extreme sensitivity of fresh Roman cements to moisture, absolutely dry aggregates (sands) should be used. This is an important prerequisite to obtain the highest possible early strength. After the mortar has been poured into the mould, the exothermic reactions should produce a temperature increase in the cast of up to around 40°C within several minutes. Under such conditions, the cast elements can be removed from the mould after about 30 min. The final strength of Roman cement mortars develops over a prolonged period of time; therefore storage of castings at humid conditions, favouring the progress of cement hydration, is essential.

Citric acid can be used to retard setting and extend the workable time to at least several minutes. The dosage should be 0.2–0.5% in water, which corresponds to 0.13–0.32% related to the weight of the cement.

14.8.2 Rendering and Run Work

The grand stuccoes of the 19th century always contained linear or oval mouldings, like cornices, obtained by applying in situ the mortar and repeatedly passing a profile over them. Renders, usually rusticated or lined out with false joints, were used to imitate stone details and textures. It was usual to produce the stuccoes in two or more coats, the inner coat being a coarse-grained ‘core’ on which a fine-grained thinner finish layer was applied. Roman cement was a preferred material to execute the stuccoes due to its quick setting which facilitated progress of the process.

The mortar design for the in situ stucco work differs from that for casting described above. The mortars should obviously contain a larger proportion of the aggregate filler; for the base coat the optimum cement to aggregate ratio is 1:1.5 by volume, for the finish coat 1:1. The aggregates are commonly sands, quite coarse for the base coat (grain sizes up to 4 mm but concentrated around 0.25 mm), finer for the finish layer. A good consistency is obtained with a water to cement ratio of about 0.6.

The workable time has to be considerably extended for the in situ work. Therefore, the retarder (citric acid) should be added at the concentration of 0.5% in water, which corresponded to 0.3% of the weight of the cement. The workable time is then around 30 min which is sufficient for an experienced practitioner to render several square metres. The surface can be worked to produce the required texture or a close polished finish within an additional 1 h or so.

Prior to the application, the surface must be well wetted not to take water from the stucco mass. As observed many times for historic renders, Roman cement mortars can be applied as a single coat in an astonishing range of thicknesses from 3 to 60 mm.

14.8.3 Restoration of Roman Cement Stuccoes

Nineteenth and early 20th century buildings deserve the same good conservation approach as objects from earlier periods. Unfortunately, they have long been undervalued as purely utilitarian constructions and therefore have been vulnerable to frequent renovation and redecoration measures which would have had little concern for the requirements of good conservation. The proper remedial strategy for Roman cement stuccoes must take into consideration several aspects:

Fig. 14.11 Stripping existing modern masonry paint with the use of superheated water

14.8.3.1 Cleaning and Uncovering

First of all it should be recalled that paint layers need not affect the original building materials adversely as long as they are in a good state of preservation. The decision to remove paints or to clean surfaces is therefore frequently an aesthetic rather than a technical question.

There is no basis for the frequently encountered concern that façade materials can be damaged by cleaning with the use of water (Fig. 14.11). The close, sound surface of Roman cement stuccoes, especially of cast elements, has a relatively low water absorption capacity. On the other hand, these are highly porous in their bulk and quickly release the absorbed water.

Thus, the removal of polymer-bound paints is best performed by using superheated water systems, while mineral paints and surface coatings require a low pressure abrasive cleaning by a swirling action of a mixture of air, water and fine mineral powder. Stubborn residues require hand cleaning with the use of fine mechanical tools. In such cases, full cleaning of a façade is not feasible, at least on economic grounds, and the façade is usually painted over.

14.8.3.2 Grouting and Injection of Cracks

The network of fine cracks, so characteristic of Roman cement stuccoes, usually does not pose any threat. The same is true of the frequent hollow spaces between the render and the masonry. However, when it is necessary to stabilise the detached areas, grouting can be carried out using a mixture of Roman cement with water to the required consistency, possibly with the addition of a surfactant. After flushing out the void with water, the grout is introduced. Cleaned and dampened cracks can be also effectively filled and stabilised by a Roman cement-water grout. Unlike synthetic resins, however, it will not glue together loose fragments.

Fig. 14.12 Repair of damages

14.8.3.3 Repair of Damages

The repair mortar should be designed to match the colour and texture of the host material (Fig. 14.12). A range of aggregates must therefore be first tested in terms of grading, composition and amount. The composition can be varied with cement content in the range 1–3 parts by volume which would produce mortars of a required strength compatible with the original stucco. Surfaces of a repaired cavity should be painted with a slurry of mortar to achieve a good adhesion of the repair. If necessary, a dispersion of polymers commonly used in restoration, can be used for the same purpose. The repair should be kept moist for a period of time to assist proper hardening. Due to its high water retention within the fresh mortar and the capacity to continue hardening at elevated relative humidity, self-desiccation of Roman cement mortars is unlikely to occur.

14.8.3.4 Surface Coatings

Where the stucco was originally coloured to imitate stonework, the colour is to be applied to a cleaned and repaired surface. The paint treatment should produce a translucent coating of high durability and the colour should be matched to surviving original examples. Unpainted Roman cement façades can be coated with a thin layer of Roman cement wash, if an aesthetic re-integration of stained and eroded surfaces is necessary.

14.9 Conclusions

The principal achievement of conservation science in the last 10 years is re-establishing the use of Roman cements in conservation practice. With the ready availability of Roman cements the family of historic hydraulic binders, necessary for the appropriate conservation of the built heritage of the 19th and 20th centuries, is now complete; we no longer need to turn to substitutes for help. It can be hoped that use of Roman cement based mortars and washes in the restoration of historic buildings of the period will meet with a growing acceptance on the grounds of performance of these unique binders:

They are an authentic historic material and technology compatible with the original stuccoes.

Roman cements extend the range of natural historic binders of varying hydraulicity available for conservation practice—lime→hydraulic lime→natural cement.

They optimally match the colours and textures of the historic host materials.

They are universal binders enabling restorers to produce a range of decorative elements on the facades of buildings from architectural castings to plain renders.

They are pure salt-free material.

They can be applied in thick layers due to low shrinkage.

The Roman cement mortars combine high strength with high porosity which assures good transport of water and water vapour.

The historic Roman cement stuccoes and renders of a wide range of aggregate content exhibit excellent durability.

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Chapter 15
Historic Mortars and Plasters as a Material for Age Determination

Danuta Nawrocka, Tomasz Goslar and Anna Pazdur

15.1 Introduction

The time range of the construction of a given historical building may be determined by various methods. Applying methods of relative chronology makes it possible to establish the wall sequence, and the different stages of development. The artifacts, ornaments characteristic of a given epoch, or the inscriptions on the walls are valuable sources of information. Carbonate binding materials, including mortars and plasters provide an opportunity to use the radiocarbon method for age determination of buildings. The processes of mortar and plaster production run similarly, comprising the application of appropriate fillers and additives, which depend on their future use. They are mixtures of binder and aggregate in different proportions. Mortars are materials which cement the elements of a given building; whereas plasters are the finishing materials, forming layers covering walls, columns and ceilings. Both the mortars and the plasters are directly connected with a given historical object. Mortars are clearly linked with the time of building erection, whereas the age of plasters may represent different phases of renovation. Field studies and subsequent material analyses coupled with their characterisation are important preparatory steps before dating.

The basic process of mortars and plasters production takes place according to the following reactions:

$$\mathrm{CaCO_3} \xrightarrow{T} \mathrm{CaO} + \mathrm{CO_2}$$

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2}$$

$$\mathrm{Ca(OH)_2} + \mathrm{CO_2} \rightarrow \mathrm{CaCO_3} + \mathrm{H_2O}$$

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The first phase consists in limestone burning, which results in so-called *burnt lime* (reaction 1). The burnt lime is subsequently quenched with water giving so-called *slaked lime* (reaction 2). This semi-product after mixing with sand (aggregate) and water becomes easy to lay and when exposed to air, gradually binds and hardens, due to absorption of atmospheric CO_2 (reaction 3). In such a case, a ^{14}C date of the binder of the mortar should reflect the age of its production, and hence, of the erection of a given building. However, problems arise in the occurrence of fragments of unburnt limestones, which form the admixture of so called dead carbon, i.e., carbon completely or partly devoid of active ^{14}C isotope (Folk and Valastro 1979; Hale et al. 2003; Heinemeier et al. 1997; Labeyrie and Delibrias 1964; Nawrocka et al. 2005, 2007; Sonninen and Jungner 2001).

Another complication is connected with the recrystallisation and slow hardening of binder resulting in too recent dates (Baxter and Walton 1970; Folk and Valastro 1979; Sonninen et al. 1985). However, this does not occur in the present group of samples.

Here, we outline the difficulties of mortar and plaster ^{14}C dating using the samples from Hippos, a settlement located by the Sea of Galilee. The samples have been made available by Prof. Młynarczyk, Dr Burdajewicz and Prof. Segal, the archaeologists who investigated this region. They established the settlement existence to a span from the 3rd century B.C. till the earthquake in 749AD (Młynarczyk 2000; Segal et al. 2004). In the Roman period the settlement belonged to the Dekapolis group. The majority of samples were taken from the walls of the north-western church (NWC), while the rest from the north-eastern church (NEC) and the buildings surrounding them. The existence of the NWC has been estimated as between 5–6th and 8th century A.D., and was erected on the ruins of an older pagan temple.

The attempt has been made to eliminate the difficulties mentioned of binding materials radiocarbon dating by appropriate sample selection, based on petrographic analyses followed by the application of different preparation techniques for the chosen group, among them the methodology proposed by Sonninen and Jungner (2001). Their study of grain size dependence of the reaction rates, point to the possibility to date in only, e.g., two fractions, by selecting a well-defined grain size window and applying calculated corrections to reach reliable dates. In the present paper the technique proposed by Sonninen and Jungner was not applied in its entirety. This method was successfully used by Lindroos et al. (2007) to correct for the influence of the different carbonates generations for the samples from Åland Islands, SW Finland.

15.2 Mortars and Plasters Characterization

A group of over 200 samples of mortars and plasters were collected for analysis. The X-ray diffraction analyses and petrographic investigations demonstrated the carbonate character of the majority of the samples and the gypsum composition of the remaining mortars (Fig. 15.1). So far, only a few samples have been identi-

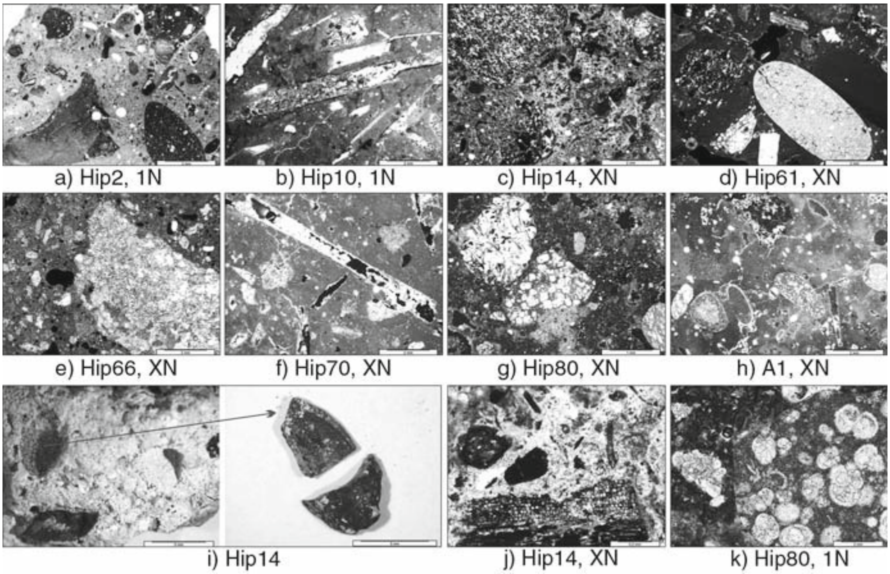

Fig. 15.1 Photographs of selected samples; **a–h,j,k**-microphotographs (polarising microscope Olympus AX70Prons); carbonate mortar samples, with basaltic-carbonate aggregate (**a,c,d,g,h**); carbonate plasters with spaces after straw (**b,f,h**); gypsum mortar (**e**); i -macrophotograph, oval fragments of charcoal from sample Hip14 (**i**); visible fragments of many charcoals in sample 14 (**j**); foraminiferous limestone in sample Hip80 (**k**)

fied as being made of gypsum (e.g., Hip62, 66, 72, 77). Their correlation with the relative chronology of the walls leads to the supposition that this kind of mortar represents the older material. The precise identification of the type and quality of the aggregate has been carried out using macro- and microscopic observations. The binding materials from Hippos usually contain basaltic-carbonate aggregate with fragments of charcoal and crushed ceramics in case of reservoirs. Parts of carbonate plasters were devoid of aggregate or contained only a small admixture of it, and the skeleton was built of straw fragments (e.g., Hip10, 70). Identification of the components of the mortar and plaster enabled the selection of samples likely to be suitable for dating (Fig. 15.1). Sample Hip2 has been taken from the collection pool in the agricultural installation to the south of the diakonikon; sample Hip10 from the southern aisle, by the balustrade, northern face of the NWC; sample Hip14 from the "floor pour" (a layer of the floor made to level uneven floor) of the channel exposed at the chancel area; sample Hip61 from the façade of the northern wall pastophorium; sample Hip70 from the passage between the main and northern aisles, the pier at the western wall; sample Hip80 from the inner walls of the tomb. All those samples were taken from the NWC and its vicinity. The sample of the plaster from the neighbouring church has also been collected (NEC, A1). The samples Hip2, 14, and 61 are building mortars, while samples Hip10, 70, 80 and A1 are finishing plasters. Sample Hip66 has not been dated, as it represented the group of gypsum mortars.

The sample Hip10 is made of pure lime, using the technology based on mixing grout with grass or straw. The plaster samples Hip70 and A1 differ from the former group by having 10–15% content of aggregate but indicate a similar production technique, relying on straw utilization. The sample Hip80 is characterised by the enormous amount of foraminifera debris used as aggregate. The sample Hip14 is a mortar forming the “floor pour” and it is characterized by the presence of small charcoal fragments, high porosity and an increased amount of aggregate. The mortar sample Hip61 is different from the rest because of a higher amount of coarse-grained sandy aggregate, mainly of the carbonate type. Sample Hip66, is completely different regarding its mineral composition, being made of gypsum.

15.3 Test Distributions of Carbonates

The important question in radiocarbon dating of carbonate binding materials is the elimination of so called “dead carbon”, connected with the presence of carbonate aggregate in the mortar. To address this problem, a special piece of a vacuum line has been prepared in the Poznań ^{14}C Laboratory. It enables the collection of several portions of CO_2 evolving from a leached sample at different time intervals. Before performing the ^{14}C measurements, observations on the course of the leaching reaction for different granulation of carbonates were carried out (after Sonninen and Jungner 2001).

The purpose of those experiments was to find the fraction most convenient for ^{14}C dating and to establish the time intervals for the chosen samples. The fractions were searched to allow collection of the portion of gas appropriate for dating, which will simultaneously be devoid of “old” aggregate. The diversified samples have been selected for the tests, in order to observe the biggest potential range of changes during the course of the reaction. Using the methodology described, the test distributions have been performed for the samples with different fractions (here: 80–100 μm, whole mortars, aggregate; Fig. 15.2).

The course of the leaching reaction for the samples from Hippos (Fig. 15.2) reveals some tendency in the distribution of all fraction samples. For the majority, the acid leaching reaction at the very beginning runs very fast and intensively—these are the portions of gas rich in CO_2 from the binder. After some time the speed of reaction slows down. The distribution results confirm the dependencies between carbonate binder, aggregate and reaction rate demonstrated by Sonninen and Jungner (2001). The performed distribution tests of the bulk samples, their fractions and the aggregate show that the more compact and harder fragments of the aggregate react with orthophosphoric acid slower than the less resistant binder. The diagram chosen shows the dependence of the reaction rate on grain size (Fig. 15.2).

Taking into account one mortar sample, the binder reacts faster than the aggregate and bulk sample. Analysing the whole samples group, this tendency has an exception—Hip80-sample with foraminiferous limestone as aggregate.

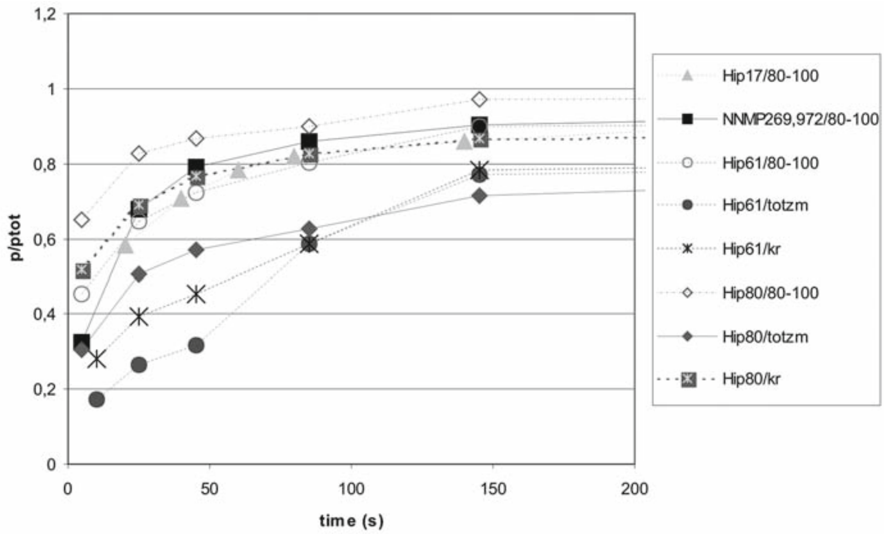

Fig. 15.2 Dependency diagram of the collected CO_2 as a function of time. Dependence of reaction rate on type of dissolved material; p_{tot} = total CO_2 pressure at the end of reaction, p = CO_2 pressure at specific time intervals for a given reaction; Hip61/totzm—sample name and dated fraction, tot-whole mortar, zm-powdered sample, 80–100-fraction of 80–100 μm; kr-carbonate aggregate

Test distributions of carbonates from other settlements together with ^{14}C measurements of chosen fractions (Sonninen and Jungner 2001; Nawrocka and Goslar in preparation Goslar et al. 2009) show that the speed of reaction increases with decrease in grain size. For the very small fractions, below 45 μm, the reaction takes place very fast, both in the case of the binder and the aggregate. Thus, the material forwarded for dating should be adjusted to the composition and size of the aggregate in a given sample. The tests performed indicate that not only the fraction by itself, but also the time of gas collection has a tremendous importance. Taking into consideration petrographic observations, the samples clearly display the enormous influence of the carbonate components of the aggregate on the reaction course. For the majority of the samples with similar composition to Hippos ones, a sufficient approach would be the rejection of the finest fraction and dating of the ranges 45–63 μm and 63–80 μm, or in the case of the samples with coarse aggregate (e.g., Hip61) also the fraction 80–100 μm.

15.4 Sample Selection for Dating

The sample preparation for dating is performed, depending on the studied material, using the procedure established in a given laboratory. The samples of mortars and plasters from Hippos have been dated by the ^{14}C accelerator technique (AMS) as well as the gas proportional counter technique (GPC). The bulk samples (binder +

aggregate) and the separated fractions of binder and fragments of charcoal were all selected for dating. In the case of the sample Hip2, in which the basalt-carbonate aggregate had a relatively large size compared to the rest of the samples, and the sample Hip70, containing a small admixture of aggregate, the bulk samples have been processed, collecting the CO_2 during the first 5 s of leaching. This procedure has been based on the assumption that old carbonate aggregate reacts slower than binder.

A slightly different approach has been used for the sample Hip61. The basaltic fragments covered with thin film of binder have been extracted and acid leaching was performed until the end of the reaction in order to collect an appropriate amount of gas for AMS measurement. The same sample, after separation of the 80–100 µm fraction and the whole aggregate-binder mixture, has also been dated by GPC technique. Double dating has also been conducted for the sample Hip10—a pure carbonate plaster devoid of aggregate, containing only voids after straw, and sample Hip80—a whole mortar mixture and separated fraction >45–100 µm. From the sample Hip2, apart from the binder also the charcoal separated from the mortar has been dated.

Because of the high content of aggregate in the sample Hip14, only a fragment of charcoal has been forwarded for dating. The selection of the charcoal fragments was preceded by an attempt at identification. It turned out that the investigated wood fragments from the excavations as well as the charcoals came from coniferous trees. They are fragments of Lebanese cedars or firs, which were difficult for unequivocal determination due to their size and state of preservation. Besides, in the mortar Hip14, oval-shaped charcoals have been found. They are difficult to identify, although they probably represent some single-year form. In the context of radiocarbon dating they constitute perfect material, due to the limited possibility of age over-estimation, which may concern wood fragments.

All these samples came from the NW church and its nearest vicinity. Only one sample—A1—was taken in the main aisle of the NE church. It is a plaster containing voids after straw and a small amount of aggregate. After microscopic observations, the fraction 45–100 µm has been chosen for dating.

15.5 Radiocarbon Dating Results

Radiocarbon dating of the mortars and plasters from Hippos (Table 15.1) was carried out by the AMS technique in the Poznań Radiocarbon Laboratory and by the GPC technique in the Gliwice Laboratory. The age calibration has been performed with the OxCal v.3.10 programme (Bronk Ramsey 2005). The probability distribution was supplemented by the information about the earthquake in 749 A.D. (Marco et al. 2003). After that disaster, the settlement had never been rebuilt. This event determines the so-called *terminus ante quem* (TAQ), thus no sample should be younger than the year 749 A.D. The radiocarbon ages have been compared with the bound-

Table 15.1 Results of radiocarbon dating (Nawrocka et al. 2007). The $\delta^{13}C$ values in the case of AMS ages were obtained after the sample preparation for radiocarbon measurement by accelerator technique. They do not indicate carbon fractionation during the mortar binding process. In the case of the dating by GPC technique, i.e., of the big samples, the $\delta^{13}C$ were obtained independently from the analysis of the part of each sample by the mass spectrometry method and they indicate the level of carbon isotope fractionation in the process of mortar binding. The low delta ^{13}C value for charcoal sample (dated by AMS) is connected with the small size of the sample—below 1 mg of C. Lab code: Gd-sample dated by GPC technique in Gliwice; Poz- sample dated by AMS technique in the Poznan Laboratory

Sample name	Archaeological context	Type of dated material	Time intervals of CO_2 collection	Lab. code	$\delta^{13}C$ (‰)	^{14}C age (BP)
Hip61	facade of the pastophorium northern wall	Mortar with coarse-grained, mainly carbonate aggregate; powdered bulk material (sk totzm)	till the end of acid leaching reaction	Gd-12824	−7.41	7140±90
Hip80	Inner walls of the tomb	plaster with foraminifera debris; powdered bulk material (sk totzm)	till the end of leaching reaction	Gd-15888	−14.52	5680±100
		fraction 45–100 µm	till the end of leaching reaction	Gd-16373	–	3340±160
Hip14	floor pour of channel exposed at the chancel area	charcoal from mortar	–	Poz-5088	−42.9	2025±80
Hip70	passage between the main and northern aisle; NWC	plaster with low (10%) content of basaltic-carbonate aggregate; pieces of bulk sample	first 5 s	Gd-12830	−11.45	1645±35
Hip2	collection pool in the agricultural installation to the south of the diakonikon	charcoal from plaster	–	Poz-5087	−42.4	1570±70
Hip61	facade of the pastophorium northern wall	basaltic aggregate covered with a film of binder	till the end of leaching reaction of binder (15 s)	Poz-16078	0.2	1490±30
Hip2	collection pool in the agricultural installation to the south of the diakonikon	sample with relatively big size basaltic-carbonate aggregate; pieces of bulk sample	first 5 s	Poz-5016	−10.8	1295±30

Table 15.1 (continued)

Sample name	Archaeological context	Type of dated material	Time intervals of CO_2 collection	Lab. code	$\delta^{13}C$ (‰)	^{14}C age (BP)
A1	NE church, plaster from the apse	plaster with low (15%) content of basaltic-carbonate aggregate; fraction 45–100 μm	till the end of leaching reaction	Gd-17381	−14.45	1140±130
Hip61	façade of the pastophorium northern wall	fraction 80–100 μm	till the end of leaching reaction	Gd-18388	−7.41	1080±100
Hip10	southern aisle, by the balustrade, northern face; NWC	pure lime plaster; powdered bulk sample	10 s	Poz-7417	−9.5	1245±35
		powdered bulk sample	till the end of leaching reaction	Gd-12823	−10.35	1310±45

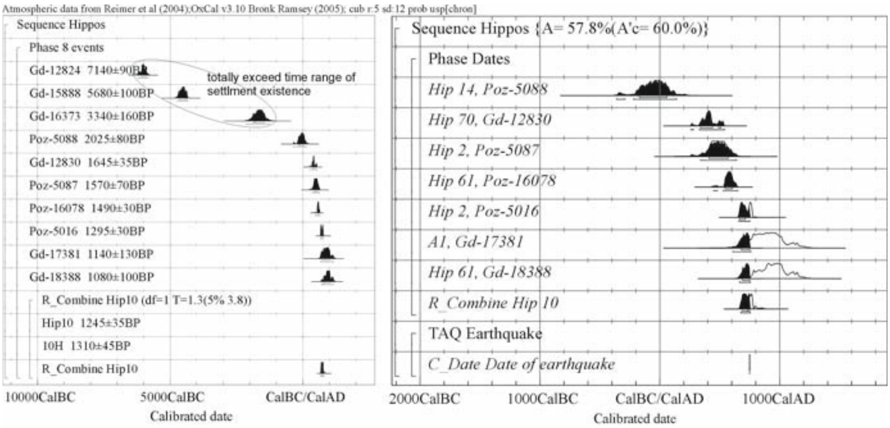

Fig. 15.3 Result of the calibration in graphical form. The results obtained for the time interval during settlement existence have been additionally analysed using TAQ options

ary age set by the earthquake. The calibration results are presented in Fig. 15.3. In the case of sample 10 the same material has been dated by two techniques and then the R_Combine option has been applied.

15.6 Discussion of Results

15.6.1 Chronology of the Buildings Studied

The results obtained from the dating of the samples from Hippos show that carbonate mortars and plasters are valuable sources of information. Due to their direct connection with the building, they present an opportunity to determine particular phases of its development. The results of radiocarbon measurements for the Hippos settlement usually coincide with the archaeological interpretation of the walls uncovered during excavations. One exception is the sample Hip80, from which small and brittle shells of foraminifera could not be eliminated. Two bulk samples (61 and 80) dated by GPC show the influence of carbonate aggregate on radiocarbon dating. The results obtained have been calibrated. All the accessible information has been applied to get the probability distribution. The sample Hip10 has been dated by two techniques: AMS and GPC (Gd-12823, 1310±45 and Poz-7417, 1245±35). Because the ages come from the same sample, they were combined using the R_Combine option. The Chi-square test, performed automatically with the OxCal programme, confirmed the compatibility of the ages (T = 1.3 (5% 3.8)). In the case of Hippos we know also from the historical—archaeological and geological sources (Ben-Avraham et al. 2005; Ellenblum et al. 1998; Amiran et al. 1994) that the time of ultimate settlement destruction was connected with the earthquake in 749 A.D. This information has been applied for calibration and interpretation of the dates (TAQ).

The oldest sample dated so far—Hip14—indicates after calibration 2nd cent. B.C.—1st century A.D. It comes from the reconnaissance in the main aisle of the NW church. In accordance with archaeological predictions it indicates the age of the pagan temple which was in use before the church. The dating also allows the phases of church development to be distinguished. The sample Hip70 (Gd-12830, 1645±35) can be linked with the first phase and comes from the passage between the main and the northern aisle. The twice dated sample Hip2 (Poz-5016, Poz-5087) cannot be directly classified to the second or the third phase of church development due to the probability distribution obtained after calibration. However, considering the archaeological clues, the first phase, which might be indicated by the dating result of charcoal from this sample (Poz-5087), can be excluded. To the third phase of church development the samples Hip61 (Gd-18388), A1 (Gd-17381) and the R_Combine for the sample Hip10 (Gd-12823 and Poz-7417) can be admitted.

^{14}C measurements of the plaster samples from the interiors of the NW church (Hip10) and the NE church (A1) gave similar results (Table 15.1, Fig. 15.3). Both samples are finishing plasters and the dating results indicate the third phase of the church development, the 7th to 8th centuries A.D. The results suggest that the walls of both churches might be of the same age. However, one should remember that while the age of mortars is strictly connected with the time of building construction, in the case of plasters the relation is not so straightforward. Plasters may represent different phases of building renovation and reconstruction, so they can be much younger than the building itself. These divisions correspond with the interpretation of archaeologists.

15.6.2 Reliability of ^{14}C Dates of Mortars

The methodological problem of ^{14}C dating of binding material concerns sufficient elimination of the effect of age overestimation which can be sourced to the carbonate aggregates. Depending on mortar composition, removal is possible in different ways. To verify the applied techniques of preparation and the results obtained, dating of the selected samples by two different methods, or the dating of different material from the same sample by the same method was carried out.

Two samples, Hip2 and Hip61, in which the basalt-carbonate aggregate was of a relatively big size compared to the rest of the samples, have been analysed without fraction separation. The attempt to date bulk samples (e.g., Hip2, Poz-5016) was done in order to verify if it is possible to date the sample without special preparation knowing the composition and size of its aggregate. In order to compare the results from the same sample, the charcoal has been dated (Hip2, Poz-5087). The measurement results obtained for different materials from the same sample in the case of the Hip2 as well as the Hip61 gave divergent results. The interpretation of these results together with the wall chronology indicates that for the Hip2 the result, consistent with the phases established by archaeologists, is given by the binder sample (Poz-5016, 1295±30).

This statement is confirmed also by the composition of the mortar, which along with the prevailing basaltic aggregate contained carbonate fragments. However, they were hard, compact fragments of relatively big size, which should dissolve much slower during the acid leaching. So, especially important is the fact that the portion of CO_2 collected from this sample for dating came from the first 5 s of reaction. The age obtained from the dating of charcoal from this sample is older than the binder age. Because there are no visible traces of recrystallization, which might have caused under-estimation of the obtained binder age, one should suppose that the charcoal age was overestimated. The charcoal fragments might have come from the older period and have been accidentally mixed into the sample, or they could represent the older parts of tree trunks.

Among the samples from Hippos studied, two charcoals have been chosen for dating—the above-mentioned Hip2 (Poz-5087) and Hip14 (Poz-5088). For the sample Hip14 the dating result coincides exactly with the wall chronology and the archaeological interpretation. The situation is different in the case of Hip2. It can be explained by the differences between the charcoal fragments selected for dating. The attempt to identify them indicated two types of charcoal. The first group is formed from wood of coniferous trees—firs or Lebanese cedars, probably being fragments of large trunks. Such fragments, if coming from the trunk centre will be significantly exaggerated in relation to building age. To the second group belong oval single-year forms, devoid of the age over-estimation possibility. From the sample Hip14 such an oval charcoal fragment has been dated. In the sample Hip2 the analogical elements have not been found and the dated charcoal probably was a tree trunk fragment.

The sample Hip61 contained mainly carbonate aggregate, built of massive pelitic and oncolithic limestones. Thereby, only the fragments of basaltic aggregate covered with a thin film of binder have been selected for dating. Contrary to the Hip2, for Hip61 the collection of a sufficient amount of CO_2 in a short leaching time was impossible. The observed ^{14}C age being too old may thus be linked to the time of leaching. Perhaps in the case of a bigger reaction vessel, which could contain a larger amount of aggregate fragments and collect a sufficient gas portion after 5 s, the result would be closer to reality. However, in the analysis performed, the time of reaction was lengthened and the leaching reaction came to an end. Thus, one must conclude that apart from the thin layer of binder covering the basaltic aggregate, the sample studied must also have contained the fragments of carbonate aggregate, which were leached during the reaction (Poz-16078, 1490±30). From the same sample the fraction 80–100 μm has been dated by GPC (Gd-18388, 1080±100). Taking into account the composition of Hip61, one would expect, the younger age obtained for the sample dated by this method appears correct.

15.7 Concluding Remarks and Summary

Binding materials, due to their direct connection with buildings, are valuable tools for the determination of the age of this type of historical object. For the mortars and plasters from Hippos, both the binders and charcoals separated from them have been ^{14}C dated. Dating of those materials is connected with some difficulties. In the case of mortars, the problems are generated by unburnt limestone fragments and different shells debris, which can cause age over-estimation. In the case of charcoals there is a risk of over-estimation in relation to the age of the building due to the peculiarities of tree growth.

Depending on the composition and content of aggregate, each sample has been prepared in a specially chosen way (bulk material, selected fractions and granulation, time intervals of acid leaching). Regarding the methodological character of the study, some samples have been dated several times using different fractions, different preparation techniques and two different techniques of ^{14}C measurement.

The mineral composition, apart from the need to recognise it for the appropriate sample selection, can also become a tool in the studies of the correlation of particular walls and the determination of the relative age of the building. The comparison of the XRD analyses and petrographic results with the plan of Hippos allowed for distinguishing the older gypsum mortars and younger carbonate mortars representing different phases of the NW church development. If the fragments of buildings of different age are preserved, there is a chance for correlation of possible variability in mineralogical composition with the radiocarbon dating results and wall stratigraphy. The investigations performed have shown that the application of mortars and plasters for the determination of the age of a building is linked with their preliminary detailed characteristics, which allows for adequate sample selection for dating. The experiments demonstrated that petrographic analyses enable a choice of the appropriate fractions for dating, as the type and size of aggregate play a crucial role. In some cases even special preparation does not make it possible to obtain the real age of mortar binding, e.g., in the case of mortars with a high content of brittle foraminiferous limestone. Despite minimalisation of the acid leaching time and choice of the specific fractions, the influence of foraminifera debris could not be removed. The ideal material for dating although rarely met in the historical buildings is the carbonate mortar devoid of carbonate aggregate and secondary recrystallization (which may give the effect of age under-estimation). The majority of mortars contain components which may cause a discrepancy between the ^{14}C age and the real age of the mortar binding. The special preparation technique based on the separation of fractions, generally allowed us to eliminate these components. For the binding materials from Hippos the best results have been obtained for the portions of CO_2 collected after the first 5 s of acid leaching in different fractions depending on composition and grain size of the aggregate in a given sample. Appropriate granulation selection may allow the real age to be obtained. An alternative is the dating of charcoals selected from mortars, especially those within a very fine carbonate aggregate, which is difficult to eliminate. In the selection of charcoal fragments proper for ^{14}C dating, its preliminary identification may be helpful. The conducted radiocarbon dating of the samples from Hippos indicated three different phases of the NW church development, mostly overlapping with the relative chronology which was established by the archaeologists.

One should remember that the dating results on different fractions and bulk sample from the same mortar (e.g., Hip61, Hip80) show that the applied separation process is quite effective, but in fact, even the shortest time of leaching may not exclude all content of "dead carbon". In that case, the correction for the influence of the different carbonate generations for the samples is necessary. In mortar radiocarbon dating, knowledge about the historical sources and archaeological context (e.g., relative dating) is quite important and enables the results to be verified.

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Chapter 16
Reinforced Concrete Constructions at the Beginning of the 20th Century: Historical Review and Structural Assessment

Mauro Mezzina, Fabrizio Palmisano and Giuseppina Uva

16.1 Introduction

Many reinforced concrete buildings and constructions belonging to the early 20th century can be found in European cities. Unfortunately, in most cases these pieces of work so rich in historical, architectural and cultural significance urgently require maintenance and restoration.

The first problem is to recognize the monumental significance of reinforced concrete architectural works in order to assure their protection and conservation and correctly define the criteria for their management. Many documents about restoration (Charter of Venice 1964; Carta della Conservazione 1987; Italian Charter of Restoration 1972) clearly outline that the concept of monument is to be intended with regard to "every age and geographical area having a significant artistic, historical and cultural interest." Anyway, attention is generally focused on ancient works, and the place of the Modern as an endangered heritage still has to be defined. Especially in the case of infrastructure or industrial constructions (that represented a very fruitful and fertile expression in the history of the development of reinforced concrete), the consciousness of their monumental significance as a historical and cultural sign is not yet perceived at a political and administrative level. Consequently, there is a severe risk of many works so rich in architectural and technical significance not surviving.

It is particularly important to study in detail these kinds of historical structure and recognize their character and constructive details, if we wish to keep the memory of the past and preserve these works for the future.

From this perspective, a brief historical journey through the development and widespread use of reinforced concrete technology is taken in this paper, paying par-

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ticular attention to the role played by the proliferation of patented systems like the one by Hennebique. Specific mention will be made of the work of the Porcheddu Society, which was one of the most representative and important dealerships of the Hennebique trademark in Italy. From 1894 to 1933, the company realized a great number of relevant projects in Italy, among which the most renowned and worth mentioning is certainly the Risorgimento Bridge on the Tevere River in Rome.

Most of the works of the Porcheddu Company were concentrated in northern Italy, but a few significant constructions were realized also in the south. This paper briefly deals with a representative example of a reinforced concrete structure in southern Italy: the Viaduct of Corso Italia in the city of Bari, which represents a model of technical excellence achieved at the beginning of the 20th century and shows the high level of accuracy and quality with regard to the design and execution. In particular, this viaduct really appears as an “artwork”, having an undeniable elegance and simplicity and endowed with great historical and cultural value as the sign of an age of great technological expectations (Mezzina et al. 2003).

When speaking of conservation and assessment of historical reinforced concrete structures, there are some interesting questions to be asked about the theoretical background available to engineering design at that time, and about the structural assessment, also in the light of more recent codes of practice.

In this sense, a crucial aspect is represented by the assessment of the shear capacity that is the subject of the last part of the paper. Indeed, the flexural behaviour was well understood, and the assessment performed by using the actual standards reveals a reliable performance. The shear capacity, instead, is much more delicate, because of many uncertainties in the theoretical approaches which often suggest resort to phenomenological and experimental modelling. Moreover, in the case of bridge structures, when a seismic assessment has to be performed by means—for example—of a pushover analysis, it is particularly important to account for the shear strength, and this requires a specific investigation of the shear performance.

16.2 A Successful Technology

From a scientific and technological standpoint, the knowledge of reinforced concrete as being a material vulnerable to the deteriorating action of time is well established, and is widely proved by experience with several reinforced concrete buildings whose poor performance is very well known to professionals.

However, only in the last few years is a perception of the problems of this endangered heritage, despite its youth, beginning to spread on a wider scale (unfortunately, because of several repeated collapses).

The extensive technical debate about the structural safety of reinforced concrete buildings is in fact opposed to a “popular” image where reinforced concrete is still considered a forefront technology, an everlasting and indefinitely resistant material. In many cases, this became the symbol of social and economic redemption:

the main desire for many people was to abandon their old and crumbling masonry houses for brand new, concrete buildings.

Even if we think of the several advantages of the material (cheapness, simplicity and rapidity in execution, fire resistance), it is very hard to explain how reinforced concrete technology was able to achieve such a rapid and overwhelming superiority in the construction field, easily ousting traditional techniques.

In the space of only one century, from the applications of the first bold inventors and experimenters at the end of the 19th century, reinforced concrete technology has become the undisputed leader of a new era of construction, a paradigm of modernity and progress (Harvey 1989). As a witticism we might define this simple combination of steel and concrete as one of those brilliant inventions that have played a fundamental role in the Second Industrial Revolution, the true philosophers' stone of the 20th century (Delhumeau 1999; Iori 2001; Nelva and Signorelli 1990).

The height of its success, actually unqualified and unopposed, was achieved in the 1950s: ancient buildings were systematically abandoned in favour of a more secure and functional residential model.

Fundamental, in order to completely understand the size of the event, is the scenario that took shape throughout all Europe after the 2nd World War:

"In the reconstruction process, Reinforced Concrete played an enormous role! We could not even imagine what would have happened without it, how many years—or decades—it would have taken to rebuild things by using the traditional techniques and materials". (From the inaugural speech at "Les journées du Centenarie" of M. Christian Pineau, Minister of Public Works, Transportation, and Tourism of France, Paris 8 November 1949 (AAVV 1949).

May be, without reinforced concrete, the extraordinary housing and economical boom of the post-war period would never have started.

16.2.1 An Everlasting Material?

Unfortunately, the too steep a climb in popularity is, to a certain extent, the reason for the partial failure of reinforced concrete technology: the speculative impulse, together with an excessive confidence in the standardization of the building process, actually induced a disregard for the quality and accuracy of the work, severely undermining the performance and durability of the structures.

Considering that in ancient times monuments were designed to last a thousand years (but also a lot of minor buildings have actually survived for many centuries), the current discussion about the restoration and structural restoration of reinforced concrete, after only one hundred years from its birth, is a sign of a failure or, at least, of a betrayal of those great expectations generated at the threshold of the 20th century. Also from a merely technological standpoint, even the slogan coined by the forerunners: "Reinforced concrete is for forever" suddenly seems to be unsuitable. Within a few years, the maintenance and restoration of reinforced concrete structures has grown into a fundamental question.

It is interesting to notice that the first flaws in one of the most beautiful hagiografical constructions ever dedicated to a composite material corresponds to the disruption of the Bureau Hennebique, in 1967 (Delhumeau 1999; Iori 2001; Nelva and Signorelli 1990).

The poor durability of the current concrete has brought this issue to the forefront, and is a new challenge for contemporary design. Actually, entire chapters of the most recent codes of practice are devoted to the definition of durability requirements, which nowadays have the same importance as resistance requirements. The question of the ageing of concrete is then the real crucial point of a modern theory of reinforced concrete.

16.3 Development of Reinforced Concrete Technology and Patented Systems in Italy

There are a number of historical precedents to reinforced concrete, and indeed concrete in itself has the same ancient and noble roots as masonry and stone constructions. Nevertheless, these precedents had only a negligible influence on the events that marked the end of the 19th century and decided the beginning of a new age for construction, within that second Industrial Revolution that was disruptively breaking into the world scene. Indeed, the appearance of the reinforced concrete system, unlike the previous building technologies, can be considered to be the fruit of a brilliant "invention" (Delhumeau 1999; Iori 2001) and not the result of a smooth and gradual development.

This is demonstrated also by the proliferation of patented systems: the most representative is surely the one registered by *Monsieur Francois Hennebique* (Fig. 16.1), whose name will be eternally associated with the development of the new material. He himself contributed, in a certain sense, to the creation of the myth of the Ingenious Inventor, not without a cunning sense of business. According to a popular anecdote, the entrepreneur *Hennebique*, while building a house in Belgium for his client, *Mr. Madoux*, happened to witness a terrible fire destroying a nearby building. So, he had a brilliant flash of inspiration and thought of a fireproof floor, made with a brand new material: reinforced concrete. The slogan of the trademark became, in fact: *Plus d'incendies désastreux*. It was the birth of an extraordinary climb to success for the man and his firm. The key to his success was his great ability in business strategy rather than the originality or intrinsic superiority of his patent in comparison with that of rival firms. Actually, many features of the patents he used to display as his personal ideas were already present in previous systems.

On the one hand, he created a very effective organization, a net of agents and dealerships spread worldwide (by 1908, he had 42 affiliates in Europe, Africa, Asia and America) that can truly be considered an *ante litteram* franchising. He also had a successful strategy of advertising and dissemination within technical, academic

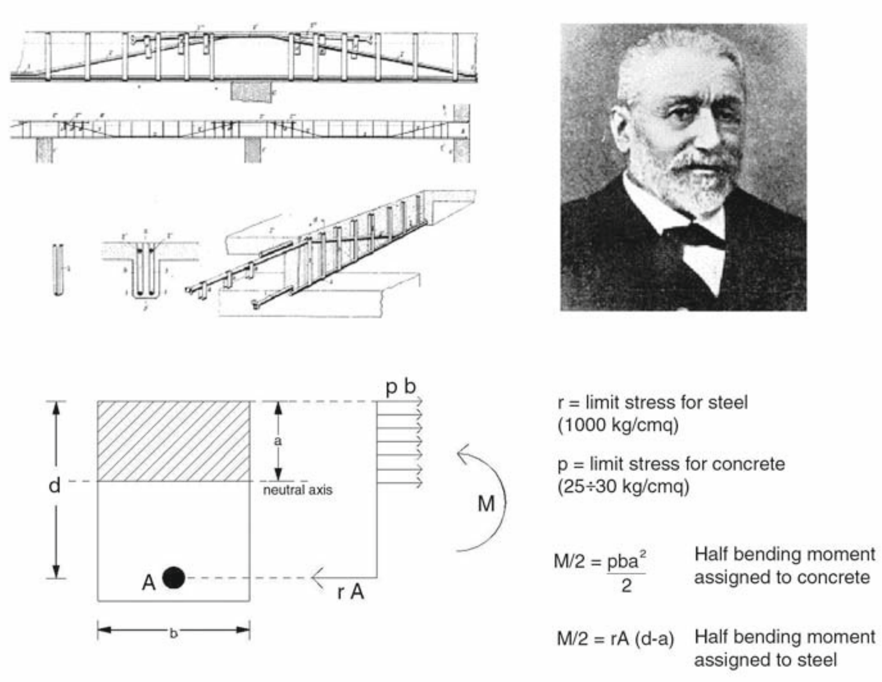


Fig. 16.1 Monsieur Francois Hennebique, his patented system and the calculation method

and political circles. He promoted technical meetings, discussions and conferences (he was the organizer of the first conference on reinforced concrete), invited professionals, academics and politicians to the construction sites, founded a technical journal (*Le Bèton Armé*) which he used to tell of the disastrous failures of his rivals. Anyway, in the course of a few years (from 1892 to 1909) he realized 20824 projects, including 1300 bridges. The unbroken success of his work strengthened his fame: as he himself liked to say: "my buildings speak for me".

The design of the structural elements subjected to bending moment is a peculiar feature of the Bureau Hennebique. Even if it was actually incorrect, the successes obtained in practical application seem to demonstrate the effectiveness of the procedure. By all means, this should be ascribed to the great sensitivity and experience of the inventor, who was able to make a guess at mechanical phenomena that were still unknown at that time.

The method was based on the equal sharing out of the work between the concrete and the iron. Half of the bending moment was taken by the concrete, and half by the reinforcements (Fig. 16.1, bottom). The unknown position of the neutral axis was determined by equating half moment and concrete stress (considered uniformly distributed and equal to 25 kg cm^{-2}). Thus, the corresponding equation applied to the steel allowed the determination of the minimum required area (assigning the value for the steel stress).

16.3.1 The Role of the Patented System After the Regulations were Issued

At the beginning of the century, the first national codes of practice were issued, in the aftermath of numerous collapses. This marked the end of the age of the pioneers of concrete technology; and finally there was a reorganization in a field dominated by personal undertaking and ability in conquering the market. Many European countries soon adopted rules for concrete constructions (1903 Switzerland, 1904 Germany, 1906 France). In Italy, the first law was enacted in 1907; and even if at the beginning it only concerned public works, it marked an important milestone, since no reference to the patented systems was made at all. It was only required that a building was designed according to the code standards, correctly carried out and well supported by a good reputation and experience of the company.

In spite of this new situation, the use of patented systems still persisted. Well established and tested technologies were still preferred and considered more reliable. The case of the Viaduct of Bari is a good example of this trend, since the Porcheddu Company managed it according to a well-tried procedure.

In what the distinctive function of the patent consisted in in this example we can only guess, since the official project was drafted according to the new prescriptions, definitely far-off from the "secret" method of calculation used for so many years by Hennebique.

Anyway, this circumstance well demonstrates the peculiar characterization of the reinforced concrete technology as a breakthrough invention, to such an extent that the forerunners and their inventions held the leading position for a long time.

Anyway, by applying the celebrated method of the "half-and-half momentum", we can find that the amount of steel needed for the section is just the same as is provided by modern calculation methods.

16.3.2 The Work of the Porcheddu Society

One of the dealerships of the Hennebique trademark in Italy, the most representative and important, was the Company G.A. Porcheddu (Fig. 16.2), operating in Italy from 1894 to 1933. This professional office had a modern and efficient organization, and autonomously developed the design activity. It is worth remembering that the Company released a number of original patents, and employed for the first time a light mixed roof made of reinforced concrete and bricks, the precursor of the modern roof still widely used in Italy. The company was the protagonist of several great and significant projects in Italy. The most renowned is certainly the Bridge Risorgimento on the Tevere River in Rome (Fig. 16.2). It spanned a single bay of a width of 100 m and for many years held the record of the longest reinforced concrete bridge.

Mostly those in Piemonte and Northern Italy, some projects were carried out in the rest of the country too, above all in the difficult years of the 1st war, when it

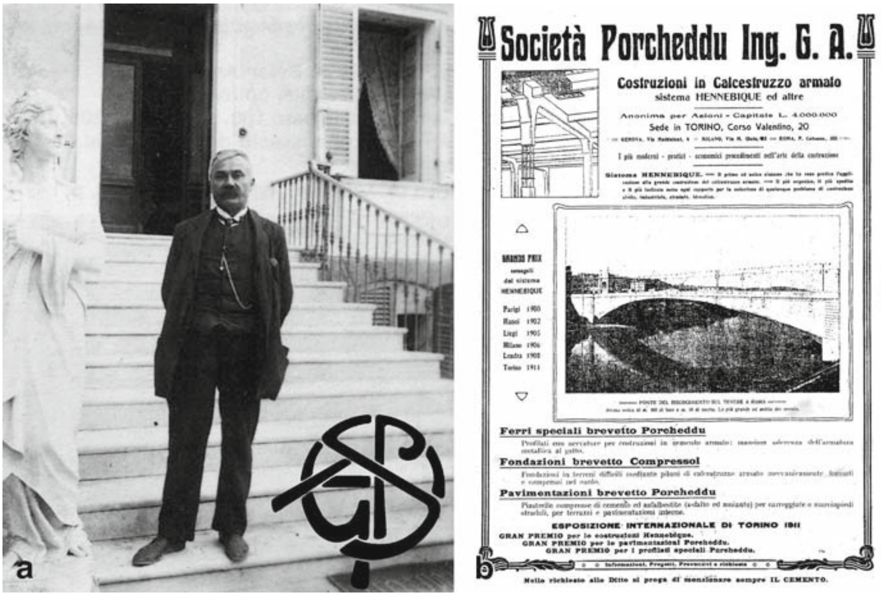


Fig. 16.2 Antonio Porcheddu (**a**) and an advertisement of his Society (**b**), showing the “Risorgimento Bridge” in Rome

remained the only Italian agent for the Hennebique trademark. In Southern Italy, the Porcheddu Company realized very few projects and the only bridge is a railway viaduct located in the city of Bari, in Puglia (Fig. 16.3).

16.3.3 The Viaduct of Corso Italia

At the beginning of 1915, the opening of a new 1,200 km railway line connecting some Italian regions (Puglia, Calabria, and Basilicata) was announced. The event was really significant from a social, economic and political point of view. In fact, it established a connection between territories geographically isolated and set apart from the economic scene ever since that time.

The whole enterprise was hard, but it was the occasion for realizing a significant example of the “modern” rising reinforced concrete technology in Southern Italy. In fact, while other bridges and viaducts throughout the line were traditional masonry or steel constructions, one of the branches—the 280 km long-line Bari-Atena—started in the city of Bari with a concrete flyover track “just like those built in the big foreign metropolises” (newspaper of the Touring club Italiano, N. 1, January 1915).

It was more than 1 km long, and indeed it was one of the first examples in Europe of a railway line set over a concrete viaduct. Surely, it was the longest in Italy and represented a technological milestone. This event was the sign of a revolution that

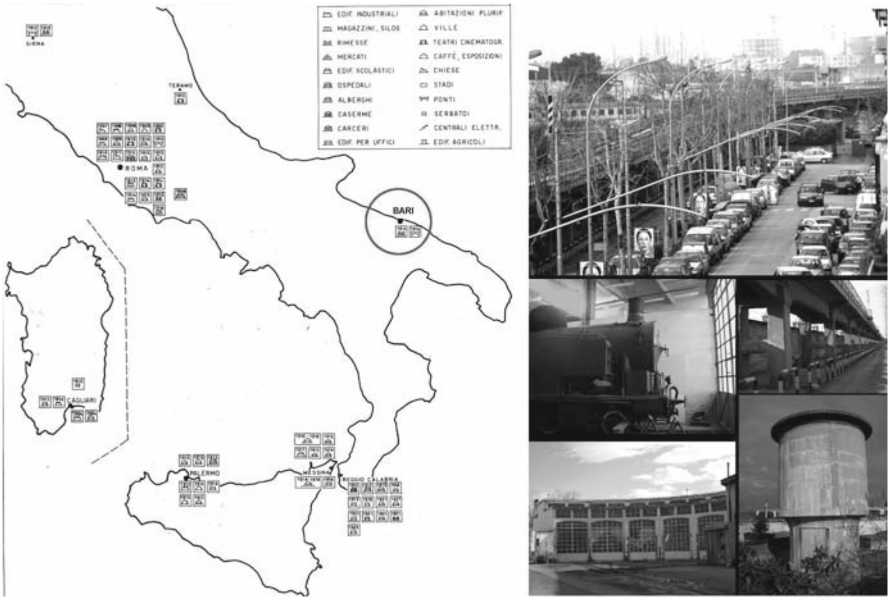


Fig. 16.3 Map of Porcheddu Society's works in Southern Italy, with an overview of the realizations in the City of Bari: the Viaduct, the hangar for steam engines and a reservoir

many European countries had already invested in and radically changed Structural Design and Architecture.

The viaduct was designed and built by the Porcheddu Company, which completed the work in only eight months of restless activity, despite the difficulties and restrictions imposed by the war (Fig. 16.4). The official test of the flyover, 1038.80 m long, took place on the 23 of July 1915, and was welcomed by the local press as a symbol of modernity and technical progress. The essential and simple (but nevertheless elegant) design showed itself to be successful, both in static performance and as an architectural solution.

The project, registered at the National Technical Office for Constructions in May 1912, provided a structural scheme with equal bays about 9 m long. After every four bays, a joint breaks the continuity of the system, allowing free thermal expansion of the spans.

The structural section that sustains the plank (3.40 m wide) is made up of two rectangular beams (60 cm wide and 100 cm high, on average) located just under the axis of the rails, and connected by a thick slab (11.5 cm) in the upper part, in order to guarantee the collaboration and transversal stiffness (Figs. 16.5 and 16.6). Finally, the system is completed by a protruding slab (that has a slant of 2.5% for rapid draining of any water) and by two edge beams holding the rail bed.

The vertical support is supplied by couples of pillars founded over a concrete plate. The supports are doubled at the dilatation joints, although founded over the same plate.

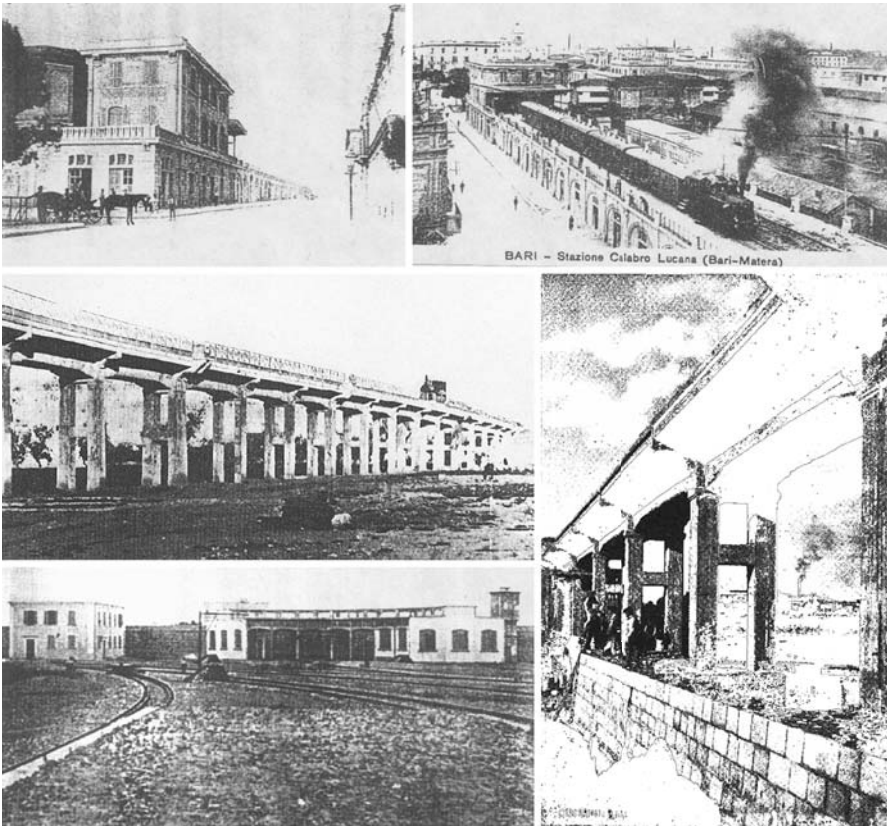


Fig. 16.4 The arc viaduct and the concrete flyover; the Hangar for steam engines (*bottom left)* (Rassegna Tecnica Pugliese 1915)

All the design was performed in accordance with the codes of practice (Regio Decreto, 1907). The work of the materials was kept to the prescribed limits, i.e., a limit stress of 1000 kg cm^{-2} for the tension in the steel (800 kg cm^{-2} for shear) and 40 kg cm^{-2} for the compression in concrete (value attained only in one case). The concrete mixture was made with rounded aggregates, and a content of 300 kg of cement per m^3.

An element of great interest in this case study is the exceptional performance shown by the concrete after almost 100 years of service life (the structure is still working perfectly!): during some repair and refurbishment works, experimental tests have shown that the mechanical strength was about 100–150 kg cm^{-2} magnitude. Technically speaking, the quality and good performance of this structure can be considered completely satisfactory: indeed this is a case study that demonstrates the effective and successful use of the technology of the time.

Looking at the original project dated 1912, it can be seen that all the calculations were made in accordance with the methods required by the codes of practice

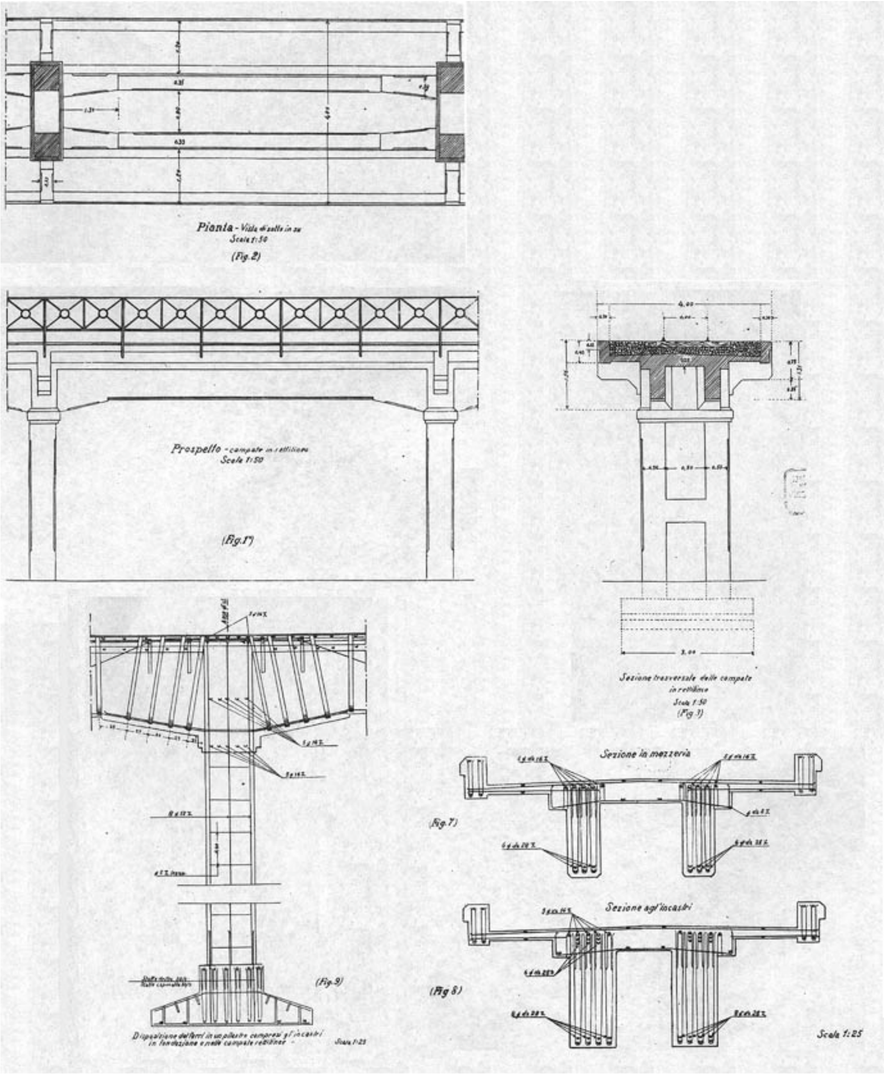


Fig. 16.5 Section of the Viaduct; detail of the reinforcements and brackets (drawing of Diaferia et al. 2003)

(indeed, not very far from the admissible stress method that is still used in Italy today). In particular, a 4-bays scheme was adopted. The dead load was estimated as 4900 kg m^{-1} (including the structural load and the roadbed), while for the live-loads two typical trains were considered, distinguishing a flexural action from a shear one and obtaining an equivalent distributed load (6820 and 7500 kg m^{-1} respectively). In order to account for the dynamic effects induced by mobile loads, a 25% increment was applied to the loads mentioned, leading to the design values of 8525 and

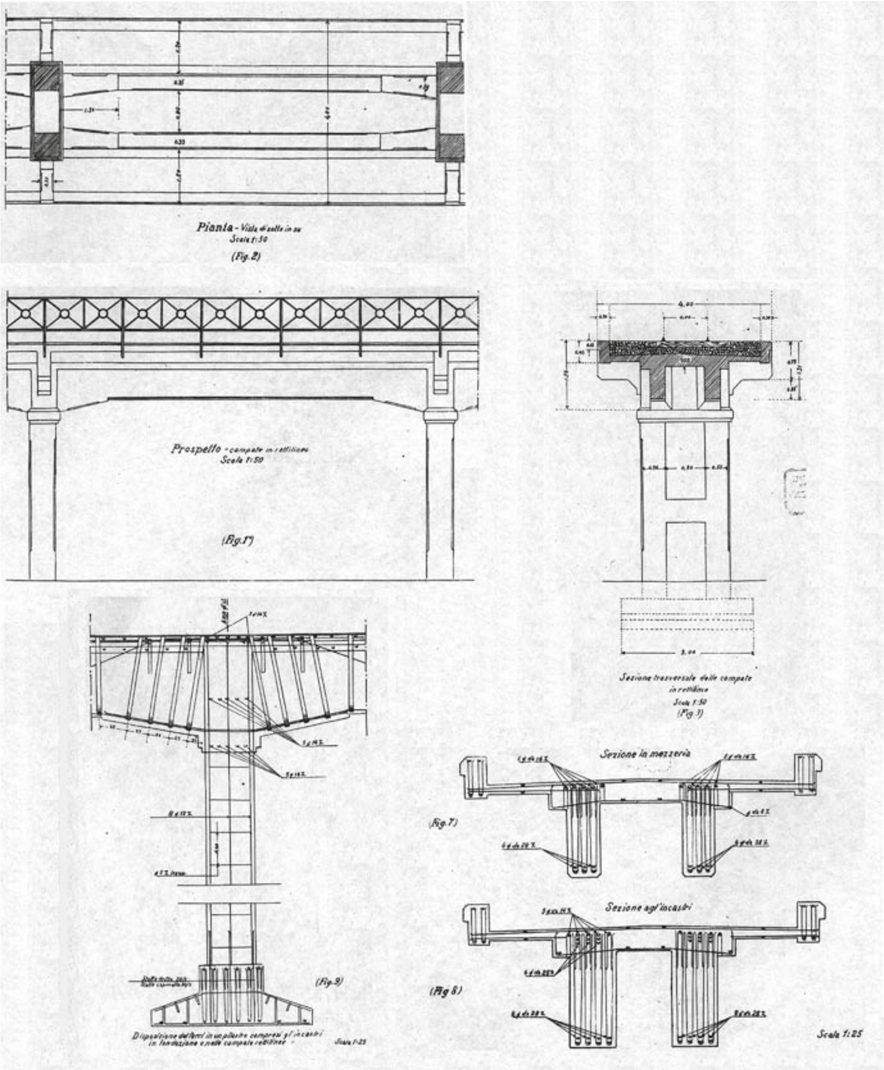


Fig. 16.6 Section of the Viaduct; detail of the reinforcements and brackets, prospect and plan view, detail of the column-beam connection (Rassegna Tecnica Pugliese 1915)

9375 kg m^{-1}. The maximum bending moment and maximum shear were found from the Winkler tables, for a continuous beam of equal bays, on five supports.

For the static calculations, two main beams were considered, having a rectangular section of 60 × 100 ÷ 120 cm. Only a portion of the upper slab (for a width of 270 cm) was considered to collaborate with the beams. Considering that the prescriptive value for the homogenization coefficient n was 10, and applying the standard calculation for the design and verification of the section, it can be seen that a minimum quantity of steel of about 150 cm^2 and an approximate height of 110 cm are required. Actually, in each main beam 4 Φ 30 straight bars were adopted, and 5 additional bent bars (Φ 35) were arranged in order to help the maximum stress zones (total amount: 152.76 cm^2). With these data, the neutral axis is 30.72 cm far from the upper edge of the section; the stress ratio is 37.8 kg m^{-2} for the concrete and 802 kg m^{-2} for the steel.

16.4 Assessment of Early Reinforced Concrete Structures: Shear Capacity

The main task to be faced in the restoration of the early reinforced concrete constructions is the assessment of their actual structural capacity, in order to provide the proper guidelines for restoration and conservation.

It is not so straightforward to apply to ancient concrete structures the same methods of calculation that are used for the new design, and this is particularly true with regard to the shear behaviour. In fact, in this case, the models and formulations which are used in the standard design practice are founded on the experimental observation of the behaviour of real scale structural elements. The constructive technique and the structural details concerning the shear reinforcement have changed much over the last century, much more than the longitudinal reinforcements.

Therefore, the approach to the question should necessarily start from a critical review of the different formulations for the shear capacity, and from an analysis of the available experimental tests on ancient structures. In this sense, great help is provided by the work of Emil Mörsch and the experimental campaign he performed in Stuttgart, which is widely described in his writings (Mörsch 1923).

A discussion and investigation about the shear behaviour of early reinforced concrete structures is a fundamental premise in order to perform the seismic assessment through a pushover analysis. In fact, in this case, the evaluation of the flexural strength must be supplemented by the determination of the shear capacity, in order to identify the actual resistance that is obviously determined by the lowest limit (Priestley et al. 1996).

16.4.1 Shear Capacity Requirements in the Contemporary Technical Codes

Chapter 11 of Annex 2 of the Italian technical standard *Ordinanza 3274* (Presidenza del Consiglio dei Ministri 2003) deals with the assessment of existing buildings. The safety evaluation of old reinforced concrete buildings usually depends on a level of uncertainty higher than the one regarding new designs. This implies the adoption of confidence factors and analysis methods that depend on the completeness and the reliability of the available information. In this field, already characterized by a high level of uncertainty, the evaluation of shear capacity of reinforced

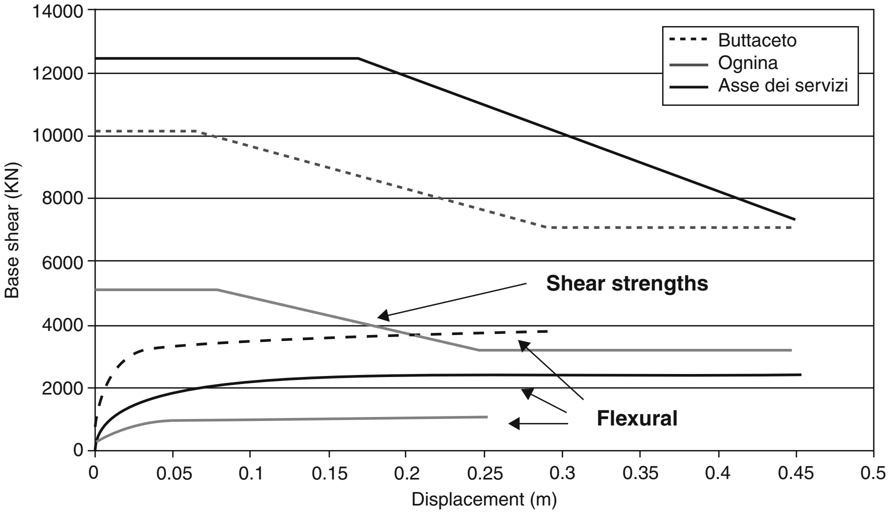


Fig. 16.7 Example of the determination of the capacity curve for a bridge: intersection between the flexural capacity curve and the shear capacity (Priestley et al. 1996)

concrete structures built in the early 20th century seems to be particularly complex. Present methods evaluating shear capacity are not applicable to old reinforced concrete structures for the following reasons:

- the chemical characteristics of the steel reinforcement and, in particular, the low Carbon content that makes the collapse cracking pattern be typical of concrete structures with high ductility reinforcement;
- the technology and, in particular, the type of shear reinforcement that consisted of open "U" shaped plates which are not able to confine the inclined struts of the resisting internal truss.

In this paragraph, starting from the tests performed in Stuttgart in the early 20th century (Mörsch 1923), a preliminary analysis of shear capacity evaluation is shown.

16.4.2 The Shear Tests Performed in Stuttgart

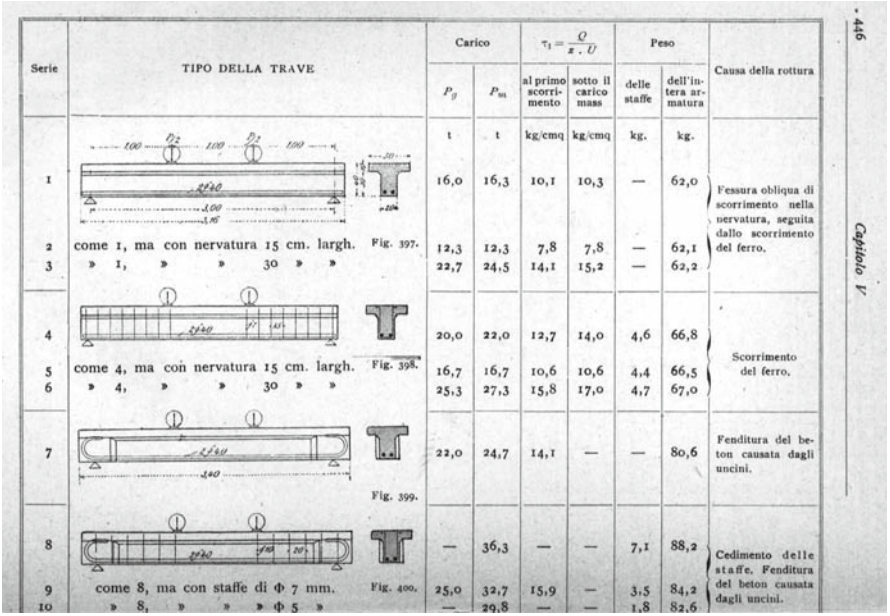
In Table 16.1 and in Fig. 16.8 data and results of some shear tests performed by Mörsch in Stuttgart from 1906 to 1921 are summarised.

In Table 16.1:

- R_c is the cubic concrete compressive strength;
- f_t is the reinforcement tensile strength;
- b_w is the web width;
- h is the overall depth of the cross section;
- ϕ_l is the longitudinal reinforcement diameter;

Table 16.1 Some shear tests performed in Stuttgart (Mörsch 1923)

	R_c (MPa)	f_c (MPa)	b_w (m)	h (m)	Φ_l (mm)	n_l	Φ_w (mm)	Shear reinf	n_w	s (m)	$V_{u,test}$	Failure type
4	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Stirrups	2	0.150	11,000.00	Sliding of bottom longitudinal bars
5	24.80	407.70	0.15	0.40	40.0	2.0	7.0	Stirrups	2	0.150	8,250.00	
6	24.80	407.70	0.30	0.40	40.0	2.0	7.0	Stirrups	2	0.150	13,650.00	
8	24.80	407.70	0.20	0.40	40.0	2.0	10.0	Stirrups	2	0.200	18,150.00	Stirrup failure
9	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Stirrups	2	0.200	16,350.00	
10	24.80	407.70	0.20	0.40	40.0	2.0	5.0	Stirrups	2	0.200	14,900.00	
11	24.80	407.70	0.20	0.40	40.0	2.0	10.0	Stirrups	2	0.150	18,800.00	Stirrup failure
12	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Stirrups	2	0.150	18,800.00	
13	24.80	407.70	0.20	0.40	40.0	2.0	5.0	Stirrups	2	0.150	16,400.00	
15	24.80	407.70	0.20	0.40	40.0	2.0	10.0	Stirrups	2	0.100	21,350.00	Stirrup failure
16	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Stirrups	2	0.100	20,000.00	
17	24.80	407.70	0.20	0.40	40.0	2.0	5.0	Stirrups	2	0.100	18,150.00	
18	24.80	407.70	0.20	0.40	40.0	2.0	5.0	Stirrups	2	0.050	20,250.00	
19	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Links	2	0.150	16,300.00	Concrete failure caused by top longitudinal bars
20	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Stirrups	2	0.150	16,850.00	
21	24.80	407.70	0.20	0.40	40.0	2.0	7.1	“U” shaped links	4	0.150	19,850.00	Stirrup failure
22	24.80	407.70	0.20	0.40	40.0	2.0	5.0	“U” shaped links	4	0.150	17,500.00	
23	24.80	407.70	0.20	0.40	40.0	2.0	7.0	Stirrups	2	0.150	15,350.00	Straightening of the hooks
75	24.80	407.70	0.20	0.50	25.0	2.0	7.0	Stirrups	2	0.090	15,250.00	Stirrup failure
77	24.80	407.70	0.20	0.50	25.0	2.0	10.1	“U” shaped links	6	0.140	18,850.00	



Serie	TIPO DELLA TRAVE		Carico		$\tau_1 = \frac{Q}{z \cdot U}$		Peso		Causa della rottura
			P_g	P_m	al primo scorrimento	sotto il carico mass	delle staffe	dell'intera armatura	
			t	t	kg/cmq	kg/cmq	kg.	kg.	
1			16,0	16,3	10,1	10,3	—	62,0	Fessura obliqua di scorrimento nella nervatura, seguita dallo scorrimento del ferro.
2	come 1, ma con nervatura 15 cm. largh.	Fig. 397.	12,3	12,3	7,8	7,8	—	62,1	
3	» 1, » » 30 » »		22,7	24,5	14,1	15,2	—	62,2	
4			20,0	22,0	12,7	14,0	4,6	66,8	Scorrimento del ferro.
5	come 4, ma con nervatura 15 cm. largh.	Fig. 398.	16,7	16,7	10,6	10,6	4,4	66,5	
6	» 4, » » 30 » »		25,3	27,3	15,8	17,0	4,7	67,0	
7		Fig. 399.	22,0	24,7	14,1	—	—	80,6	Fenditura del beton causata dagli uncini.
8			—	36,3	—	—	7,1	88,2	Cedimento delle staffe. Fenditura del beton causata dagli uncini.
9	come 8, ma con staffe di Φ 7 mm.	Fig. 400.	25,0	32,7	15,9	—	3,5	84,2	
10	» 8, » » » Φ 5 »		—	29,8	—	—	1,8	82,6	

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Fig. 16.8 Results of some shear tests performed by Mörsch in Stuttgart

- n_l is the number of longitudinal bars;
- ϕ_w is the shear reinforcement diameter;
- n_w is the number of links of shear reinforcement;
- s is the longitudinal spacing of shear reinforcement;
- $V_{u,test}$ is the ultimate shear strength of the tests.

16.4.3 Some Comments on the Tests Performed by Mörsch

The test results in Table 16.1 have been analysed using the models of the present codes. In particular, the last release of both Eurocode 2 (UNI 2005) and Italian technical standards (Ministero delle Infrastrutture e dei Trasporti 2008) adopt the 'truss model' with a variable strut angle θ. $V_{Rd,max}$ is the design value of the maximum shear force which can be sustained by the member, limited by crushing of the compression struts; and $V_{Rd,s}$ is the design value of the shear force which can be sustained by the yielding shear reinforcement:

$$V_{Rd,max} = \nu f_{cd} b_w z \frac{ctg\theta + ctg\alpha}{1 + (ctg\theta)^2} \tag{16.1}$$

$$V_{Rd,s} = f_{ywd} \frac{A_{sw}}{s} z \sin\alpha (ctg\theta + ctg\alpha) \tag{16.2}$$

where:

- α is the angle between shear reinforcement and the beam longitudinal axis perpendicular to the shear force;
- θ is the angle between the concrete compression strut and the beam axis perpendicular to the shear force;
- vf_{cd} is the compressive strength of the concrete inclined struts;
- z is the internal lever arm;
- f_{ywd} is the design yield of shear reinforcement;
- A_{sw} is the cross sectional area of the shear reinforcement.

θ should be chosen between the following recommended limits:

$$1 \leq ctg\theta \leq 2.5 \tag{16.3}$$

The value θ_d d of θ that makes the stirrups yield and, at the same time, the web concrete reach its limiting compression can be obtained setting the relations (16.1) and (16.2) equal and, in the case of $\alpha = 90°$, it results in the equation:

$$ctg\theta_d = \sqrt{\frac{vf_{cd} b_w}{f_{ywd} \frac{A_{SW}}{s}} - 1} \tag{16.4}$$

Coefficient v is an efficiency factor which allows for the actual distribution of the stress within the inclined struts and the effect of cracking. This factor is defined by technical standards and is calibrated on the reinforcement details prescribed in the codes. For example, Eurocode 2 (UNI 2005) assumes:

$$v = 0.60 \left[1 - \frac{f_{ck}}{250} \right] \tag{16.5}$$

where f_{ck} (in MPa) is the characteristic compressive cylinder strength of concrete.

16.4.4 *Test Ultimate Shear Strength* vs. *Code Ultimate Shear Strength*

In order to verify the reliability of the relations recommended in the present codes with respect to failure loads measured in the tests, numerical analyses have been performed using the ultimate resistance values of the materials.

The following data were adopted:

- ultimate values of the material strength;
- $R_c = 24.80$ mPa;
- $f_c = 0.83 \cdot R_c = 20.58$ mPa (compressive cylinder strength of concrete);
- $f_t = 407.70$ mPa;

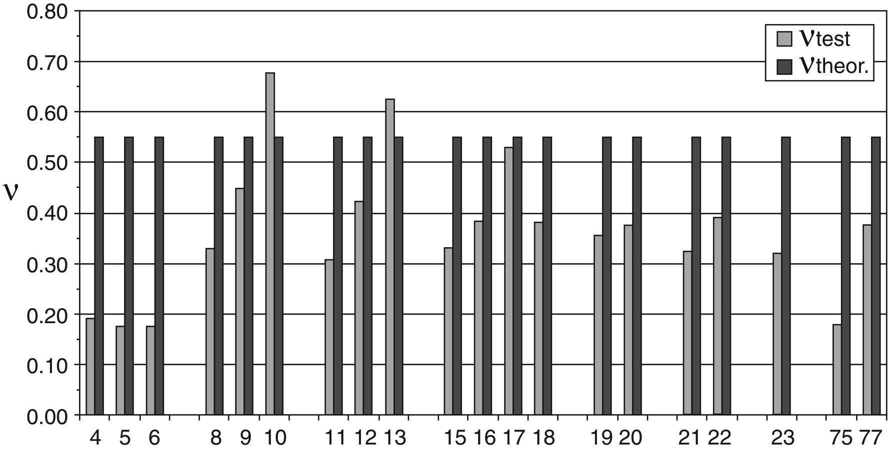


Fig. 16.9 v_{test} and $v_{theor.}$

- c_{inf} = 2.0 cm (bottom cover on longitudinal reinforcement).
- $z = 0.90\ d$ (where z is the internal lever arm and d is the effective depth of the cross section).

From Eqs. (16.1), (16.2), (16.4), assuming that the theoretical shear strength is equal to the test shear strength, the value v_{test} of v has been evaluated. Figure 16.9 shows that, almost in all the examined cases, the calculated theoretical value $v_{theor.}$ of v is bigger than the one (v_{test}) calculated from the test ultimate load.

In Fig. 16.10 the values of the test ultimate shear $V_{u,test}$ and of the theoretical one $V_{Rd,ctg\theta}$ (calculated using relations (16.1), (16.2), (16.3), (16.5) according to Eurocode 2 (UNI 2005), ignoring the limits on $ctg\theta$) are shown. The histogram in Fig. 16.10 highlights the fact that the theoretical value overestimates, almost in all the cases, the test ultimate shear strength.

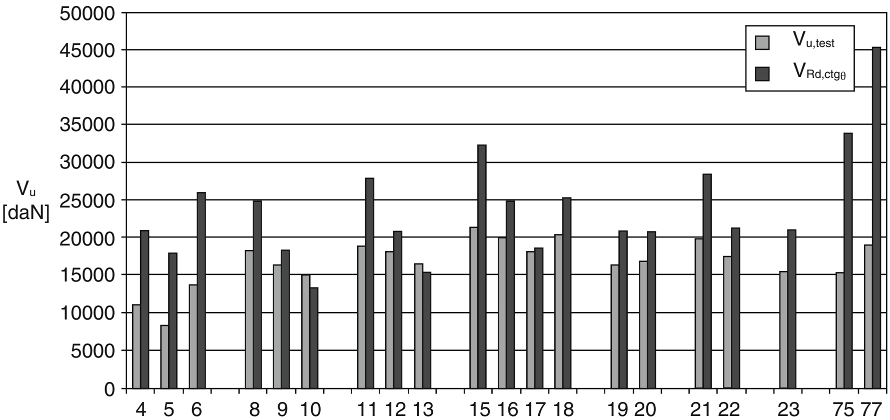


Fig. 16.10 $V_{u,test}$ and $V_{Rd,ctg\theta}$

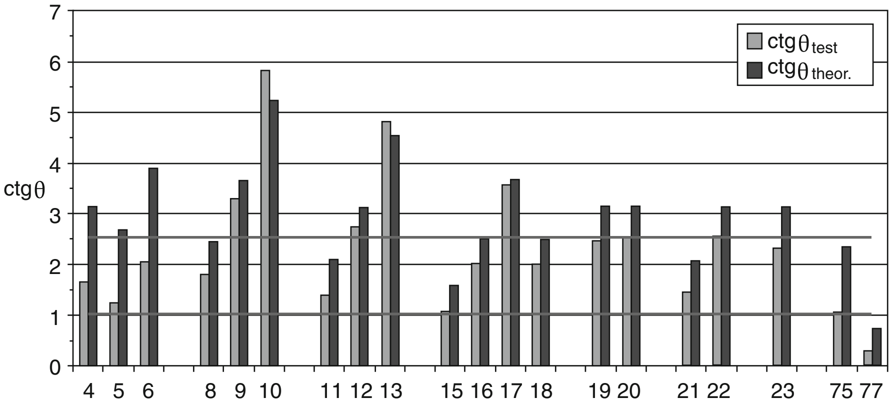


Fig. 16.11 $ctg\theta_{theor.}$ and $ctg\theta_{test}$ (red lines indicate the limits according to Eurocode 2)

Figure 16.11 shows that, almost in all the examined cases, the theoretical value ($ctg\theta_{theor.}$) of $ctg\theta$ is higher than the one ($ctg\theta_{test}$) calculated from the test ultimate load. Thus, it follows that the beams tested by Mörsch in the early 20th century did not have the capacity to reach the values of $ctg\theta$ recommended by the present codes.

It is worth noting that the 'truss model with variable strut angle', that in the Eurocode (UNI 2005), but also in the Italian code (Ministero delle Infrastrutture e dei Trasporti 2008) has substituted the 'modified hyperstatic truss model' (Palmisano and Raffaele 2007), is principally based on the following assumptions:

- the ultimate resistance of the inclined struts should be reached when the shear reinforcement has yielded;
- shear reinforcement should have the capacity to limit the opening of the cracks in order to make them be crossed by struts having an inclination θ lower than the one corresponding to the first cracking.

The second assumption could not be satisfied by reinforced concrete beams of the early 20th century. Steel reinforcement used in the past had ductility characteristics higher than the present reinforcement. This means that, because of the large deformations consequent to yielding, crack widths are so excessive as to make impossible the transfer of shear forces across them. Consequently the 'truss model with a variable strut angle' with the present limit of the maximum value of $ctg\theta$ is not by a long way applicable to beams of the past. It is worth highlighting this consideration because the present codes that deal with the assessment of existing structures use the same shear strength relations adopted for new building design. However it is necessary to differentiate the approach, trying to find the values of the maximum limit of $ctg\theta$ consistent with the test results reported in the literature regarding beams having reinforcement similar to the ones used in the early 20th century.

In the draft version (UNI 1993) (no more in force) of Eurocode 2, as in the previous Italian technical standards (Ministero dei Lavori Pubblici 1996), shear capacity was evaluated using the 'modified hyperstatic truss model' (Palmisano and Raffaele 2007).

According to this approach the shear resistance is evaluated under the assumption of $\theta = 45°$, evaluating the web tension strength separately from the web compressive strength. In particular the first one is the summation of the concrete strength (V_{cd}) and of the shear reinforcement strength (V_{yd}):

$$V_{Rd,s} = V_{cd} + V_{yd} \tag{16.6}$$

Many codes used to assume V_{cd} equal to the value calculated for the beams without shear resistance. This assumption, generally on the safe side, is difficult to justify because it is based on the hypothesis that in the element with shear reinforcement the 'dowel effect' and the 'aggregate interlocking effect' give the same contribution that they would give if the element had no shear reinforcement. Besides, when the beam has shear reinforcement, the flexural resistance of the 'concrete cantilever' between two following cracks is strongly reduced by the very low spacing of the shear cracks; this means that the contribution of the 'concrete cantilever' resistance (Palmisano and Raffaele 2007) to the shear strength in a beam with shear reinforcement is less than the one in a beam without shear reinforcement. Especially because of the difficulty of evaluating the contribution of V_{cd} in the relation (16.6), the present codes have adopted the 'truss model with variable strut angle' in which the resistance of the 'concrete cantilever' is not considered (the contribution of V_{cd} misses) and web tension strength is only due to shear reinforcement; but, at the same time, inclined struts can have $\theta \leq 45°$. This model seems to be more consistent with the results of tests performed on present beams but, as previously shown, seems to lose reliability for beams of the early 20th century.

To compare these two models, for the beams of Table 16.1, web tension shear strength $V_{Rd3,ENV1992\text{-}1\text{-}1}$ has been calculated using the ultimate resistance values of the materials and according to the 'modified hyperstatic truss model' of the old draft of Eurocode 2 (UNI 1993):

$$V_{Rd3,ENV1992-1-1} = V_{Rd1} + V_{wd} \tag{16.7}$$

where

- $V_{wd} = f_{ywd} \frac{A_{SW}}{s} z$;
- $V_{Rd1} = \tau_{Rd} \cdot k \cdot (1.2 + 40 \cdot \rho_{ld}) \cdot b_w \cdot d$;
- $\tau_{Rd} = 0.25 \cdot f_{ctm}$;
- $f_{ctm} = 0.30 \cdot f_{ck}^{2/3}$;
- $k = (1.6 - d) \geq 1.0$ (d in m);
- $\rho_{ld} = \frac{A_{sl}}{b_w \cdot d} \leq 0.02$;
- A_{sl} is the area of the tensile reinforcement, which extends not less then (l_{bd}+d) beyond the section considered (with l_{bd} design anchorage length of reinforcement).

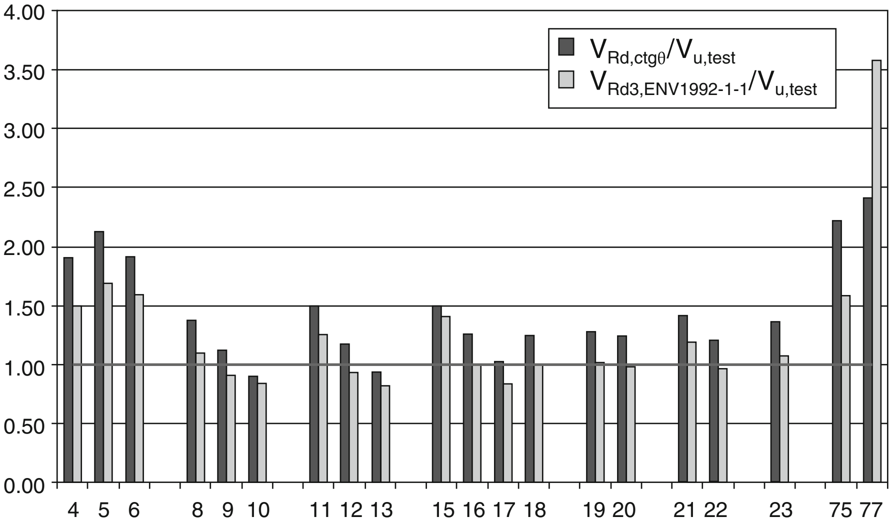


Fig. 16.12 Ratio of the shear capacity ($V_{Rd,ctg\theta}$) according to Eurocode 2 (UNI 2005) and of the web tension shear strength ($V_{Rd3,ENV1992\text{-}1\text{-}1}$) according to the old draft of Eurocode 2 (UNI 1993) to the test ultimate shear strength ($V_{u,test}$)

From Fig. 16.12 it is worth noting that, almost in all the cases examined, the 'modified hyperstatic truss model' of the old draft of Eurocode 2 (UNI 1993), confirming what was previously discussed, gives results that are more similar to those of the laboratory tests.

16.4.5 The Transversal Shear Behaviour

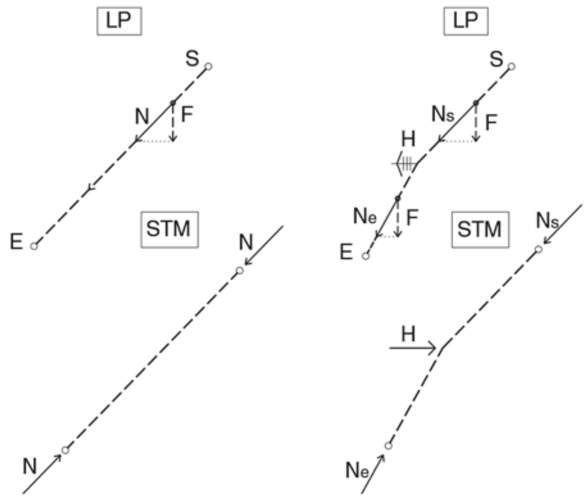
In this paragraph the interpretation of transversal shear behaviour is shown using the Load Path Method.

Originating as a method of designing Strut-and-Tie Models in reinforced concrete structures, the Load Path Method (whose basic principles are more widely illustrated in Mezzina et al. 2007; Palmisano et al. 2007) is a clear and effective technical instrument of investigation and judgement.

In the transfer of forces within a structure, or member or element, from their point of origin (*S*) to their ends (*E*), deviations in the load path direction can occur causing a thrust (*H*); for equilibrium to be maintained, a reactive force must be applied that is equal in magnitude and opposite in direction to this thrust (Figs. 16.13 and 16.14).

The load path represents the line along which a force or a force component (more precisely: the component of a force in a chosen direction, e.g., the vertical component of a load) is carried through a structure from the point of loading to its support. The force component (*F* in Figs. 16.13 and 16.14) associated with a load path remains constant on its way through the structure; as a consequence of this defini-

Fig. 16.13 Load Path (LP) and Strut-and-Tie Model (STM)



tion, thrust (*H*) must be perpendicular to the travelling load (*F*). The design of this load flowing through the structure can be approximated by polygonal lines in which there are thrusts in every deviation node. The structure will be crossed by fluxes in compression (dashed lines, Figs. 16.13 and 16.14), when loads travel in the same direction of their path, and by fluxes in tension (continuous lines, Figs. 16.13 and 16.14) along which loads go in the opposite direction respect to their path. According to the classical theory, the basic principles of Load Path Method are the respect of equilibrium and consistency. Thrusts in deviation nodes are necessary in order to respect equilibrium and every path is possible if it is equilibrated.

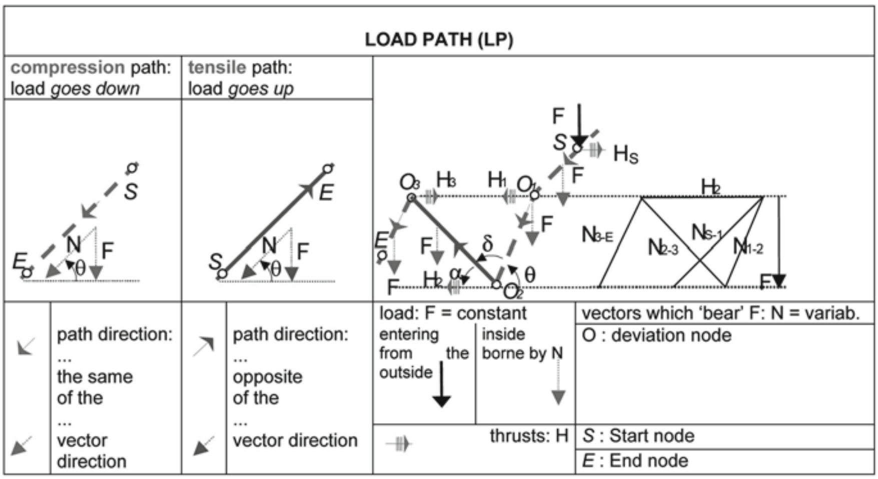


Fig. 16.14 Load Path: symbols

Among infinite paths in equilibrium, loads have to choose the one in which their vectors invest the minimum quantity of strain energy (D), that is the only one that is consistent and in equilibrium. For this purpose loads get energy from their own potential energy that decreases.

The total invested strain energy is

$$D = \frac{1}{2}\int_V \sigma \varepsilon dV \tag{16.8}$$

where V is the integration domain; σ and ε are the stress and the strain vector respectively.

Along a generic path (polygonal in this model), the calculus of the invested strain energy (D) is simplified in the summation of the terms relative to each side of the truss:

$$D = \sum_i D_i \tag{16.9}$$

where (i) is the generic side of the load path.

If linear elastic constitute laws for materials are considered, the elementary strain energy (D_i) can be written, for some typical cases, according to Fig. 16.15.

A simplified model of the diagonal compressive flux in an element subjected to shear and bending is showed in Fig. 16.16 (Mezzina et al. 2007). The flux starts from the longitudinal compression zone (on the top of the beam in Fig. 16.16) and,

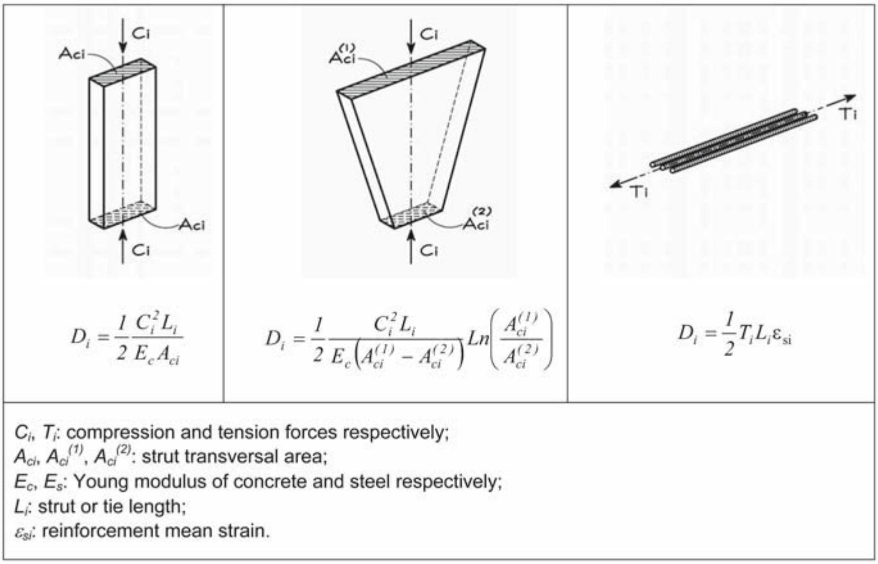


Fig. 16.15 Elastic strain energy in some typical cases of struts and ties

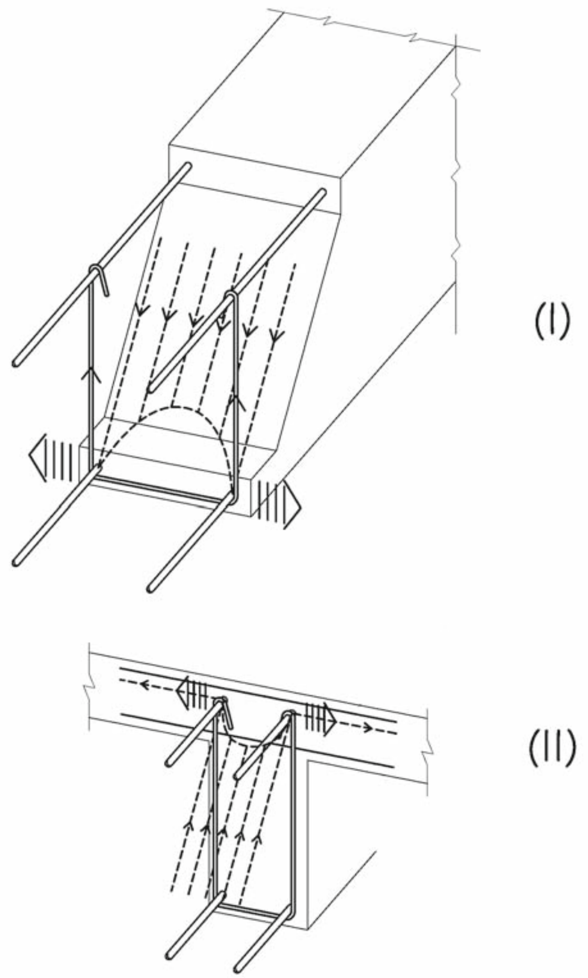


Fig. 16.16 Shear transversal behaviour of a beam (axonometric view)

in the descending path, it keeps itself spread in all the web width in order to save strain energy. However, it is obliged to concentrate on the longitudinal bars that are the only ones able to carry the horizontal longitudinal thrusts due to the deviation of the shear path. This concentration can happen thanks to the formation of a transversal arch; in this model, transversal thrusts arise and they can find equilibrium because of the transversal horizontal link of the stirrup. In the absence of this link the only way, for these thrusts, to find equilibrium is to use the concrete tension strength. Detail (II) of Fig. 16.16 shows that the presence of a floor slab, giving a compression path to the transversal top thrusts, make possible the adoption of top open stirrups.

Beams of the early 20th century often had "U" shaped links as stirrups (Fig. 16.17); this means that, for the transversal bottom thrust, equilibrium can be maintained only thanks to concrete tension strength.

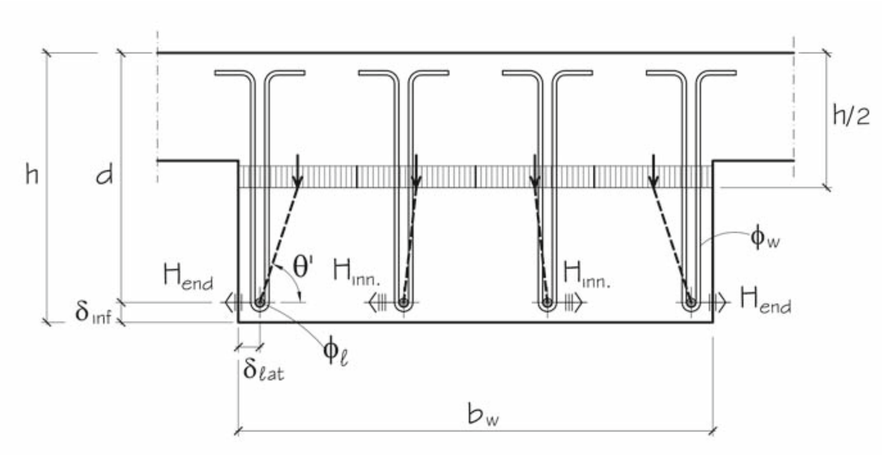


Fig. 16.17 Analysis model of shear transversal behaviour of a beam with "U" shaped links

Figure 16.17 shows a model for analysing transversal behaviour for beams with "U" shaped links. The most critical condition is where bottom lateral transversal thrust (H_{end}) is applied. The ultimate shear for the transversal behaviour ($V_{Rd,lat}$) is given by the capacity of concrete cover to carry the transversal thrusts using its tensile strength and avoiding the ejection of the longitudinal bars.

In this model the following assumptions have been made:

a) $cgt\theta'$ should not be less than an assumed value $cgt\theta'_{min}$;
b) the deviation of the inclined struts in the bottom of the beam web starts from a distance h/2 (Fig. 16.17) from the top of the beam if $cgt\theta' > cgt\theta'_{min}$;
c) the stress in the inclined strut is constant;
d) the forces in every "U" shaped link are equal;
e) H_{end} divided itself into two identical parts (Fig. 16.18): one crosses a_{sup} and the other one crosses a_{inf};
f) γ is the angle of the transversal (Fig. 16.18) and longitudinal (Fig. 16.19) diffusion of H_{end} within the concrete.

The reason for the assumption (a) is that, if the overall depth of the beam is very large with respect to its width, the inclined strut, in order to save strain energy, tends to deviate in the bottom of the beam; a limit on the minimum value of $ctg\theta$ needs to take account of this consideration. This limit could be taken equal to that ($cgt\theta'_{min}$ = 0.5) usually assumed in the design of deep beams and column footings.

As a consequence of assumptions (c) and (d), the inclined strut should be divided into a number of parts equal to the number of "U" shaped links.

The resistance of the concrete cover is governed by the minimum value ($a_{transv,min}$) between a_{sup} and a_{inf} (Fig. 16.18). Because of the assumption (e) the strength value $H_{end,max}$ of H_{end} is

$$H_{end,max} = f_{ctd} \cdot (2 \cdot a_{transv,min}) \cdot a_{long,min} \tag{16.10}$$

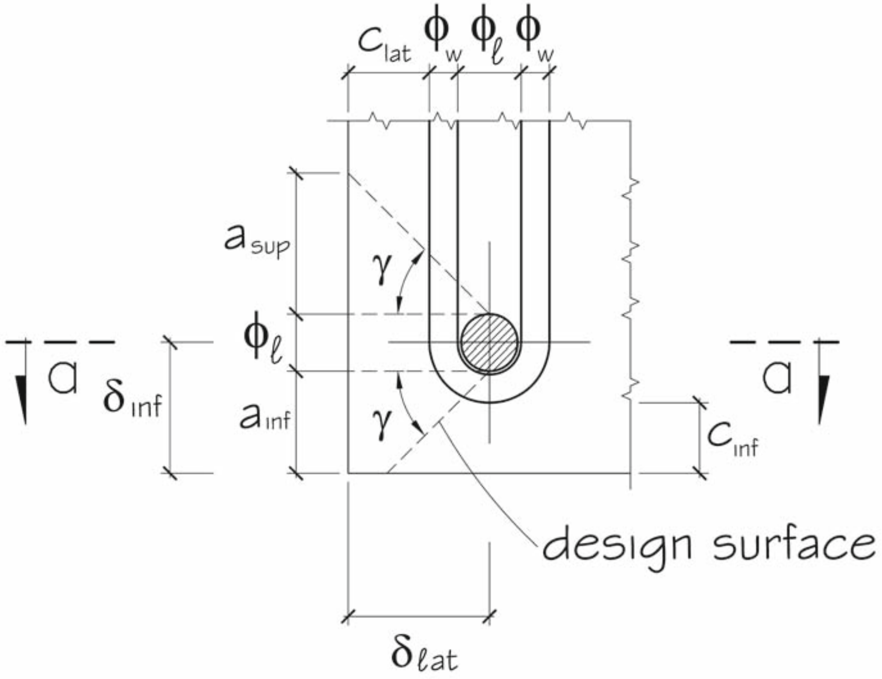


Fig. 16.18 Left bottom node detail of the beam in Fig. 16.17

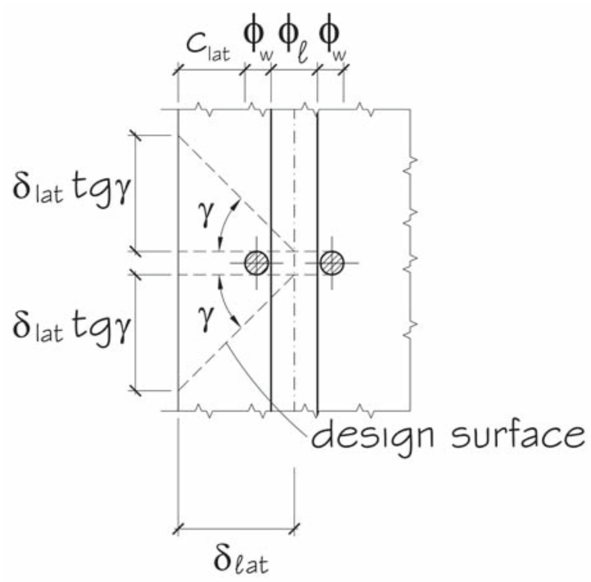


Fig. 16.19 Transversal section of the detail in Fig. 16.18

where:

- f_{ctd} is the design value of the axial tensile strength of concrete;
- $a_{long,min} = min\left[2 \cdot \delta_{lat} \cdot tg\gamma; (s - \phi_w)\right]$ is the longitudinal width of the diffusion area of H_{end};
- $\delta_{lat} = c_{lat} + \phi_w + \frac{\phi_l}{2}$;
- s is the longitudinal spacing of shear reinforcement;
- ϕ_w is the shear reinforcement diameter.

Because of the assumption (d) the total force $F_{s,max}$ carried by a stirrup composed by a total number n_w of links is

$$F_{s,max} = H_{end,max} \frac{n_w}{2} \frac{1}{ctg\theta'} \tag{16.11}$$

and the ultimate shear of the transversal behaviour is ($V_{Rd,lat}$)

$$V_{Rd,lat} = F_{s,max} \frac{z}{s} ctg\theta_d \tag{16.12}$$

where $ctg\theta_d$ d is given by relation (16.4) and z is the internal lever arm.

An application of this model is shown in Figs. 16.20 and 16.21. The following data have been used:

- design values of the material strength;
- R_{ck} = 20 mPa (characteristic compressive cubic strength of concrete);

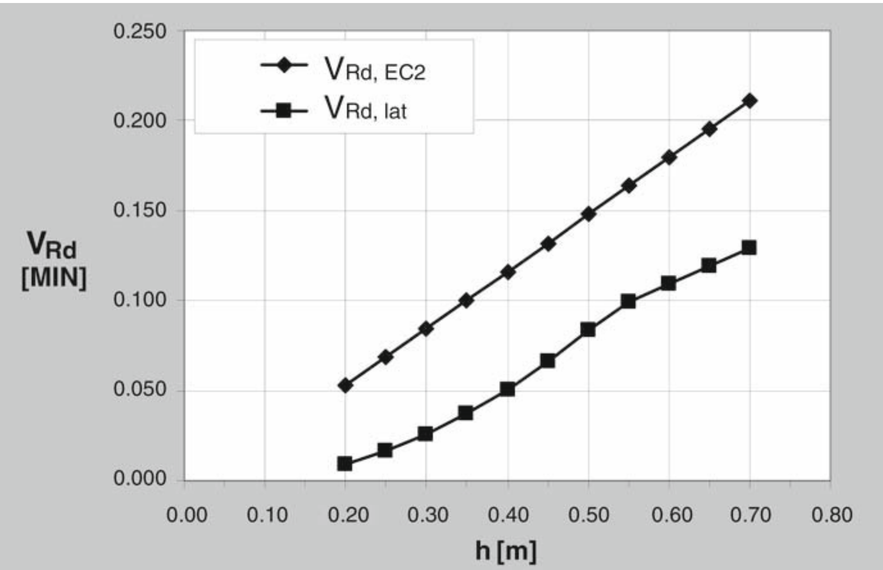


Fig. 16.20 $V_{Rd,EC2}$ and $V_{Rd,lat}$ for a beam with b_w = 30 cm and h = var.

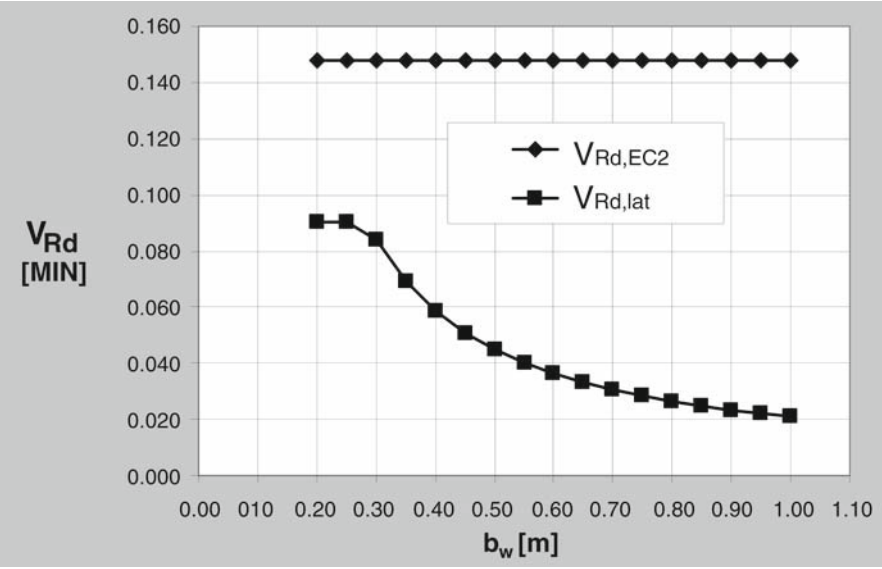


Fig. 16.21 $V_{Rd,EC2}$ and $V_{Rd,lat}$ for a beam with b_w = var. and h = 50 cm

- $f_{ck} = 0.83 \cdot R_{ck} = 16.60$ mPa (characteristic compressive cylinder strength of concrete);
- $f_{cd} = 0.85 \cdot f_{ck} / 1.5 = 9.41$ mPa (design compressive strength of concrete);
- $f_{ctd} = 0.70 \cdot (0.30 \cdot f_{ck}^{2/3})/1.5 = 0.91$ mPa (design tensile strength of concrete);
- $f_{yk} = 215.00$ mPa (characteristic yield strength of reinforcement);
- $f_{yd} = f_{yk} / 1.15 = 186.96$ MPa (design yield strength of reinforcement);
- $v = 0.60\ (1 - f_{ck} / 250) = 0.56$;
- $\phi_w = 6$ mm;
- $n_w = 4$;
- $s = 15$ cm;
- $ctg\theta'_{min} = 0.5$;
- $\gamma = 45°$;
- $z = 0.90 \cdot d$ (where z is the internal lever arm and d is the effective depth of the cross section);
- $\phi_l = 16$ mm;
- $c_{lat} = 2.0$ cm;
- $c_{inf} = 2.0$ cm.

In the example of Fig. 16.20 $b_w = 30$ cm and $h = var.$, whereas $b_w = var.$ and $h =$ 50 cm in the case of Fig. 16.21.

In the aforementioned figures the comparison between the shear capacity ($V_{Rd,EC2}$) evaluated according to Eurocode 2 (UNI 2005) (which neglects the transversal behaviour) and the one ($V_{Rd,lat}$) calculated taking account only of the transversal behaviour is shown.

According to this approach, the shear capacity of the section is the minimum value between the two calculated resistances. In both cases the shear capacity is governed by the transversal behaviour.

16.5 Reinforced Concrete: Open Questions in the Diagnostics, Safety Aassessment and Structural Restoration

The structural safety of modern reinforced concrete building is nowadays a crucial exigency from many points of view. Even if in common opinion reinforced concrete has usually been considered an indefinitely strong material, a forefront technology—in a word—a paradigm of Modernity, it is nowadays acknowledged that concrete is not an everlasting material.

Despite the fine and accurate quality of the work, this technology is subject to the deteriorating action of time even more then masonry is. Moreover, awareness of the intrinsic defects caused by aging is still scarce (together with the practice of techniques and methods of analysis and restoration). As a matter of fact, the problem of restoration applied to concrete structures belongs to the contemporary age, with scientific and technical knowledge still being developed and experimented upon.

First of all, there is a generalized question about the interventions on a large scale in the existing fabric of the cities, and the following re-qualification of the urban landscape and the management of the building heritage on the territory.

In Italy, both in the historical centres and in the outskirts, there is in fact a strong presence of reinforced concrete buildings side by side with the traditional masonry constructions. Reinforced concrete architecture ranges from the first realizations (at the beginning of 19th century) to the breakthrough of concrete technology and the related building trade in the 1970s. Not always is it characterized by quality of both architectural expression and construction. In many cases, the eventual perishability of this material (a phenomenon still unknown and unexplored at that time) has now become evident and calls for urgent recovery.

Anyway, this minor but widespread building process represents a significant part of residential housing in Italian cities, for which structural safety and functional restoration stand as primary questions of scientific, social and territorial interest.

On the other hand, a lot of reinforced concrete buildings belonging to the first decades of the twentieth century have become landmarks of historical and architectural significance and can be truly considered as monuments of the Modern era. Despite the many problems of durability and maintenance affecting the material "concrete", these structures, born at the dawn of the new technology, still survive and have shown even better performance then many subsequent examples.

It is particularly important to study in detail the historical examples, and to recognize the character and the technical details of the solutions, if we wish to keep trace of the history and preserve the evidence of the architecture and the structural science of the last few years of the 19th century.

For reinforced concrete structures, it is worth observing that only quite recently has a knowledge of degradation and viscosity phenomena been acquired, and the constructive detailing aimed at providing durability accordingly adopted.

Furthermore, it should be remembered that reinforced concrete works, from the origins (in the last decades of the 19th century) until the release of the first national technical laws (in Italy, the first one was released in 1907), were built by applying patented systems (i.e., the Monnier or the Hennebique system). These systems were often a result of individual intuitions more than a fruit of coherent and established scientific and technical knowledge. This is one of the reasons why many of the structures built in those years, and still surviving, could not be considered reliable with regard to static structural safety, as it is presently understood.

As a last element, but crucial all the same, it should be pointed out that, in spite of the availability of advanced and reliable methods for the numerical and theoretical modelling of concrete, the safety assessment is characterized by a strong level of uncertainty, because of the lack of sufficient data that can be acquired about materials, building techniques, and construction details.

In professional practice this aspect is often disregarded, since unconditional confidence is usually devoted to modern materials and structural types, which the designer is used to.

But also in this case, the a posteriori comprehension of an existing object is a complex process, inevitably incomplete and defective. The designer himself, even if he would probably be able to make a reasonable approximation, would never rule on the structural response of his creation. In no way can the application of scientifically-based models in the design of a structure assure agreement between the foreseen behaviour and the actual one. In practice, structures always show more or less significant deviations from the prediction, and an undiscerning trust in theoretical models is possibly more dangerous than deceiving.

The difficult task of diagnostics is, then, to mark out the history of the building, reconstruct the geometrical, physical and mechanical features of the construction as they were designed and as they were actually realized (number and position of reinforcement bars, general arrangement of crucial nodes and sections, mechanical properties and technological characteristics of materials used).

For those buildings dating back to the period of the first experimenters and inventors of reinforced concrete, the further problem of identifying the structural type of the case examined arises. The large diffusion of many different systems in the period between the end of the 1880s and the beginning of the 20th century makes it difficult for technicians to interpret the building technique used.

The restoration procedure is always a complex process, relying on an integrated path of preliminary knowledge, analysis, decision-making and action (architectural interpretation, experimental investigation and testing, analytical modelling, choice of intervention technique). In the case of reinforced concrete, this becomes particularly tricky for various reasons.

First of all, unlike ancient constructions, a rooted tradition in restoration and repair is lacking in this field: only over the last few decades have interventions on concrete buildings have been faced up to, and this problem received in academic and scientific circles. Whereas the peculiar feature of masonry is the relative facility in being dismantled and reassembled, concrete is a monolithic material, and once a specific shape has been realized, it is a serious problem to vary it, or to intervene subsequently. Repair techniques must account for these difficulties, and innovative materials and techniques are being studied and experimented upon (concrete or metal jackets, fibre reinforced polymers, etc.). The lack of reliable technical solutions in this field clearly shows that a debate and reflection about the principles of restoration applied to reinforced concrete construction still needs to be promoted and spread.

Moreover, the results of the tests performed on the early 20th century beams show, for instance, that applications of the codes used at present to evaluate shear resistance cannot be used without any modification. Firstly, owing to the great ductility of steel reinforcement used in the past, the old beams cannot reach the values of ctgθ recommended by the present codes. Secondly, the type of shear reinforcement (i.e., open "U" shaped links) makes transversal behaviour collapse anticipate the one provided by standard formulations calibrated on beams with stirrups.

It follows that particular care has to be taken, especially because the economical and social weight of existing building assessment is becoming particularly important.

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Part IV
Monitoring the Seismic Risk

Chapter 17
Heritage Masonry Buildings and Reduction of Seismic Risk: The Case of Slovenia

Miha Tomaževič

17.1 Introduction

Not all old masonry houses are considered architectural heritage. Although historic, individual buildings are also not always considered monumental. However, as clusters of buildings, old urban and rural centres represent an architectural cultural heritage of great historical importance, giving additional value to many modern European cities. As a link between the past and present, historical centres are actively included in the urban environment, usually representing the cities' most vital parts. Unfortunately, cultural heritage buildings have not been designed to resist earthquake loads. They have been built in materials and systems which resist the compression caused by the gravity loads but not the bending and shear resulting from the earthquake ground motion. In some cases, historic buildings have been poorly maintained or, even worse, reconstructed in the past by removing important parts of their lateral load resisting systems to accommodate the urban commerce and business needs. Consequently, during earthquakes in Europe in the recent past, most of the damage to buildings occurred and deaths have resulted owing to inadequate seismic performance of heritage buildings. To avoid such consequences when subjected to expected future seismic events, the buildings in historic centres in seismic-prone regions should be adequately strengthened. Permanent occupancy is one more reason why such buildings should be upgraded to attain the same level of seismic safety as is required for new constructions. Although this is often not easily possible, every effort should be made in seismic rehabilitation campaigns to improve their resistance to a required degree.

After earthquakes damaged seismic-prone regions of Slovenia in 1974 and 1976, experimental research to study the mechanisms of seismic behaviour and causes of damage as well as to develop adequate measures for seismic rehabilitation of

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heritage buildings has been initiated also at the Slovenian National Building and Civil Engineering Institute in Ljubljana. On the basis of the analysis of damage, improved technologies for seismic rehabilitation have been developed to reduce the seismic risk. Their efficiency has been verified by laboratory and in-situ testing, as well as by earthquakes which followed in 1998 and 2004. The correlation between the amount of damage and characteristic limit states, which define the seismic behaviour, has been studied. Based on the results of these studies, the values of material safety factors and seismic load reduction factors to be considered in redesign have been proposed in accordance with the philosophy of Eurocodes. Experiences regarding the reduction of seismic risk of heritage buildings, obtained in Ljubljana, will be summarized in this contribution.

17.2 Typology and Seismic Performance of Heritage Buildings

Traditional construction materials of heritage urban and rural masonry houses in Slovenia are locally available lime-stone and slate, which in some parts of the country are replaced by clay brick. Stone-masonry walls are made of rubble or river-bed stone, built in two outer layers of irregularly sized bigger stones, with an inner infill of smaller pieces of stone, in poor mud mortar with a little lime. In the city centres and towns, the walls are made of a relatively compact mix of stone, brick and mortar, with no distinct separation between the individual layers of the walls. Regularly cut, or partly cut stone is rarely used. Connecting stones are also rare.

Typically, stone-masonry houses are 3–4 stories high in the cities and towns, whereas their height is limited to 2 stories in rural areas (Fig. 17.1a). Stone-masonry prevails also in the case of monumental architecture (Fig. 17.1b). The distribution of walls is usually uniform in both orthogonal directions; and, because of the thickness of load-bearing and cross-walls, as well as relatively small rooms, the wall/floor area ratio is large, in many cases exceeding 10%. Floor structures and lintels are traditionally wooden, without any wall-ties provided to connect the walls. Wooden floors are sometimes replaced by brick vaults above cellars, staircases and corridors. Roof structures are wooden. They are covered with ceramic tiles, sometimes laid in mortar. As a rule, the buildings are built without any foundation. Moreover, the quality of foundation walls is usually poorer than the quality of structural walls above the ground level.

Considering the response to strong earthquakes, the behaviour of heritage buildings has been generally not adequate. Although the structural typology of masonry buildings varies in different regions, their damage resulting from earthquakes can be classified in a uniform way. The following typical causes and types of damage can be identified by the analysis of the observed earthquake damage patterns:

- Lack of connection between structural walls in the case of historic buildings without wall ties results in loss of structural integrity during the earthquake. Cracks at the corners and at wall intersections represent a characteristic damage pattern. Sometimes, separation of walls and even out-of-plane collapse occurred (Fig. 17.2a);

Fig. 17.1 Typical heritage stone masonry buildings in Slovenia: **a** rural house in Posočje Region and **b** typical monumental architecture: Pišece Castle

Fig. 17.2 Typical earthquake damage to stone-masonry heritage buildings: **a** out-of-plane collapse of perimeter walls and **b** typical shear cracks in the walls

- Inadequate structural resistance. Despite the favourable structural layout of buildings in plan and good connection of walls, the quality of masonry is not good enough to prevent the walls from diagonal cracking, disintegration, and ultimate collapse (Fig. 17.2b);
- Inadequate foundation system and/or foundation soil caused partial settlements, sinking, sliding, tilting and/or overturning of buildings.

17.3 Seismic Retrofitting and Experimental Research

Based on the above observations, the following main technical criteria should be considered and technical measures applied to improving the seismic behaviour of heritage buildings:

- Structural walls should be adequately tied and connected. To ensure uniform distribution of seismic loads on the resisting walls and to prevent excessive out-of-plane vibration and collapse of the walls, floor diaphragms should be stiffened and well anchored into the walls;
- Structural walls should be uniformly distributed in both orthogonal directions of the building. They should be strengthened to resist the expected seismic loads;

– The foundation system should be capable of transferring the increased ultimate loads from the strengthened upper structure down to the soil.

Various technical measures have been developed for retrofitting heritage masonry buildings. Some of them are based on engineering judgment only and have never been actually verified. Others, however, have been verified by laboratory and/or in-situ testing. Sometimes, the retrofitted or rehabilitated buildings have even been subjected to real earthquakes, so that the validity of some methods has been verified in the real situation.

Although various technical solutions are available for strengthening heritage buildings, their applicability depends on heritage preservation and restoration requirements. Usually, a compromise between the engineering and heritage preservation demands is made, which requires application of special techniques and materials. In this regard, testing and experimental verification of the proposed methods is of relevant importance. Testing and experimental simulation of the observed seismic behaviour is generally needed:

– To obtain quantified data for structural assessment (mechanical properties of materials, structural condition, homogeneity of materials, moisture, etc.);
– To understand the seismic behaviour and develop mathematical models needed for structural redesign;
– To verify the efficiency of methods for strengthening and repair;
– To provide the basis for code requirements (e.g., reduction of design loads).

17.3.1 Improving Structural Integrity

To fully utilize the potential resistance and energy dissipation capacity, the monolithic behaviour of masonry structures should be ensured. To ensure the integrity of heritage masonry buildings during earthquakes, the walls should be tied at floor level with wall ties. At the same time, monolithic floor diaphragm action should be provided in order to distribute seismic loads onto the walls in proportion to their stiffness.

Although the idea of tying the walls is very old, not many historic masonry buildings, including those located in seismic-prone areas, are provided with adequately installed and distributed wall ties. Since 1974, when they were first applied as a seismic retrofitting measure to stone-masonry houses after the earthquake of Kozjansko (Boštjančič et al. 1976), smooth steel reinforcing bars are used as wall ties. They are placed on both sides of the walls and threaded at the ends so that they can be anchored on steel anchor plates by nuts. They are inserted below the floor structure in horizontal channels, about 4–5 cm wide, cut in the plaster up to the wall surface. It is usually not necessary to cut the walls to place the ties. If they are long, the bars are kept in their position with stirrups, placed through the holes in the wall, drilled at the level of the ties. Steel anchor plates are at least 15 mm thick. The length of the plate is slightly larger than the width of the wall, while the plate width is a minimum of 200 mm. After placing and slightly pre-stressing the ties with a key, the nuts are welded on the anchor plate. All the steel parts of the tie are protected against corrosion by paint and then plastered so that the ties are not visible.

A series of models of heritage buildings with and without wall ties have been tested on the shaking table in order to study the effect of steel ties (Tomaževič et al. 1996). A typical situation at the end of testing is shown in Fig. 17.3. As can be seen, the upper storey of the model without wall ties has disintegrated and collapsed. In the case of the model with wall ties, however, separation and disintegration of the walls was prevented. The model collapsed because of the shear failure of the load-bearing walls in the first storey.

Test results have been used to propose recommendations about ties design. Regarding the position of steel ties, two possible modes of tie action can be distinguished:

- The ties of the walls orthogonal to seismic action (transverse ties) improve the out-of-plane resistance of the walls. Together with the effective part of the wall's height, they behave similarly as reinforced concrete bond-beams. Consequently, wall ties should be designed as reinforcing steel on the tensioned side of an equivalent bond-beam, formed by a strip of the wall between the ties at both sides of the wall, with a height approximately equal to the thickness of the wall, for bending moments which develop due to out-of-plane vibration of the wall;

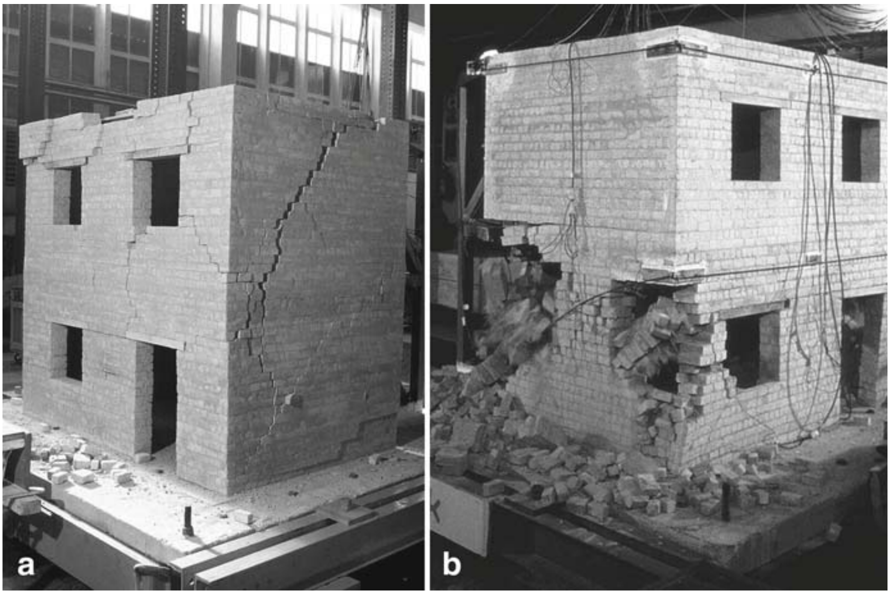

Fig. 17.3 Model shaking-table study of action of wall-ties: **a** separation of walls of control model without wall ties and **b** installation of wall ties prevented separation of walls in the upper storey

– The ties located in the direction of seismic action (longitudinal ties) prevent the separation of the walls. As indicated by the measurements, forces which develop in the longitudinal ties at ultimate state are of the same order of magnitude as the seismic shear induced in the upper structural walls.

Suitable models can be developed for the calculation. The greater value of the diameter of a wall tie, obtained by either the transverse or longitudinal action of seismic loads, should be taken into account. 16–20 mm diameter bars, used for many years in retrofit practice, seem to be adequate in the case of old masonry houses of normal size. However, in order to ensure immediate action and further improve the energy dissipation capacity, it is recommended that the wall ties are pre-stressed to half their tension capacity.

Besides traditional technologies, the methods based on new materials and technologies have also been proposed for upgrading the seismic resistance of heritage masonry buildings. Although the requirements for preservation of the cultural heritage limit their application, contemporary technologies often require minimal intervention in the existing structural system by providing substantial improvement in seismic behaviour at the same time.

The idea of replacing the usual steel ties with carbon or glass fibre reinforced polymer (CFRP or GFRP) laminate strips placed both horizontally at the level of floors and vertically at the corners of the building, has recently been studied by testing a series of models of heritage buildings on a shaking table (Tomaževič et al. 2008). As can be seen in Fig. 17.4a, in the case of the control model with wooden floors without wall ties, the upper floor disintegrated at a relatively moderate intensity of shaking. Although the strips have been placed on the outer sides of the walls only, in the confined model CFRP strips simulated horizontal and vertical ties at the level of wooden floors and at the corners of the building: they retained integrity even when subjected to seismic excitation that by more than 3.5 times exceeded the intensity of excitation causing the collapse of the control model (Fig. 17.4b). If the measured resistance curves, i.e., the relationships between the lateral resistance and storey drift of both models are compared, the resistance of the model, confined with CFRP strips, by more than a factor of three exceeded the resistance of the control model without wall ties.

It can be seen that, on the one hand, the experiments indicated the possibility of replacing the horizontal steel wall ties by CFRP laminate strips. Tests have also indicated that, where placed vertically, CFRP laminate strips additionally strengthen the structure. However, they should be properly anchored to the foundation system at the ends (Tomaževič et al. 2008). On the other hand, the experiments pointed out that technological details regarding the anchorage of CFRP laminate strips to the structural system, which is crucial for the efficiency of structural confinement, need to be resolved before the method be widely applied to heritage masonry buildings.

Earthquake damage observations and experiments indicated that the replacement of wooden floors with rigid slabs does not always guarantee improved seismic behaviour (Tomaževič et al. 1993). New reinforced concrete slabs are usually supported by the inner wythe of stone-masonry walls. However, only those parts of the

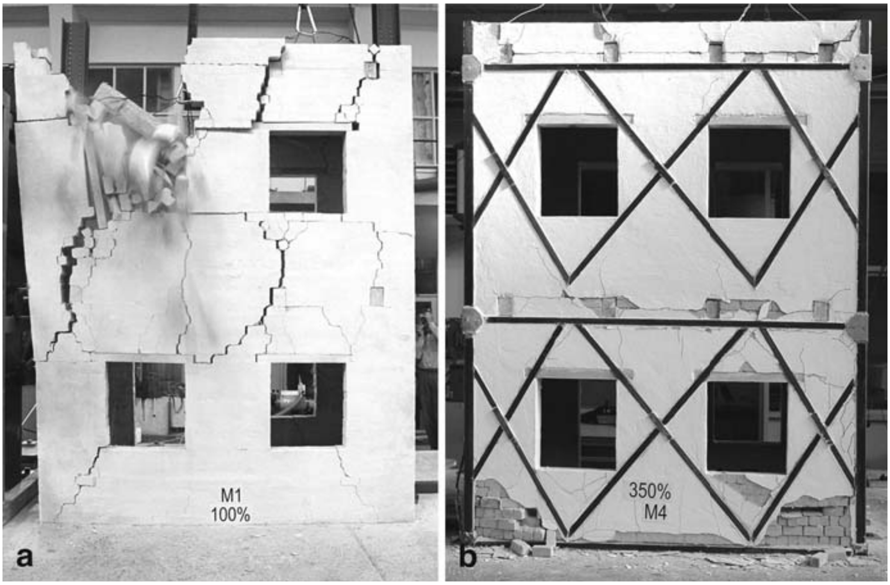

Fig. 17.4 **a** The walls of a brick masonry building model without wall ties disintegrated at moderate intensity of shaking; whereas **b** the model confined with vertically and horizontally placed CFRP laminate strips resisted 3.5 times strongest intensity of shaking

walls where the timber joists have been removed serve as supports. Besides, the slabs are not properly connected with the outer wythe of the wall. Consequently, the rigid slabs may slide on the bearing surface and cause separation, delamination and pushing out of the outer parts of the walls. In such a case, leaving the existing wooden floors in place, anchoring the joists and tying the walls with wall ties represents a much better solution.

17.3.2 Strengthening of Masonry Walls

The choice of the most suitable method to strengthen the existing masonry walls depends not only on the type and quality of masonry, but also on the required degree of improvement. The following typical methods can be used:

- repointing the joints with cement mortar;
- coating (reinforced cement, ferro-cement, FRP) on one or both sides of the walls;
- injections of cement-, lime- or epoxy-based grout;
- pre-stressing the walls in vertical and/or horizontal direction;
- reconstruction of the most damaged parts of the walls.

While various possibilities are available for the repair and strengthening of brick masonry walls, efficient interventions in stone-masonry are more or less limited to injecting the cementitious grout into the void parts of the walls.

In the case of brick masonry, coating the walls with reinforced cement or FRP laminate coatings on one or both sides of the walls is the usual method for improving lateral resistance. If reinforcing steel is used, plaster is first removed from the wall. Mortar is removed from the joints between the bricks or blocks, 10–15 mm deep, and the cracks in the wall are grouted. The wall surface is cleaned, moistened with water and spattered with cement milk. The first layer of cement coating, i.e., 10–15 mm thick cement mortar layer (compressive strength 20–30 MPa), is applied. The reinforcing mesh is then placed on both sides of the wall (4–6 mm diameter bars at 100–150 mm intervals in the vertical and horizontal directions), connected together with steel anchors (6 mm diameter bars, placed in the pre-drilled holes and cemented or epoxied, 4–6 pieces per m^2 of the wall's surface). After the reinforcing mesh is connected to the anchors, the second layer of cement coating is applied, so that the total thickness of coating does not exceed 30 mm. Depending on the quality and dimensions of the existing wall, lateral resistance can be significantly improved (Sheppard and Tomaževič 1986). In some cases the failure mechanism changes from shear in the existing to flexural in the strengthened state (Fig. 17.5a).

In a similar way, ferro-cement, and CFRP coating can be applied. For better results, reinforcement can be placed diagonally in order to follow the possible direction of cracks. Whereas similar results as in the case of conventional reinforced concrete coating have been reported with regard to the improvement of lateral resistance of brick masonry walls with ferro-cement (Prawel et al. 1988), this is not

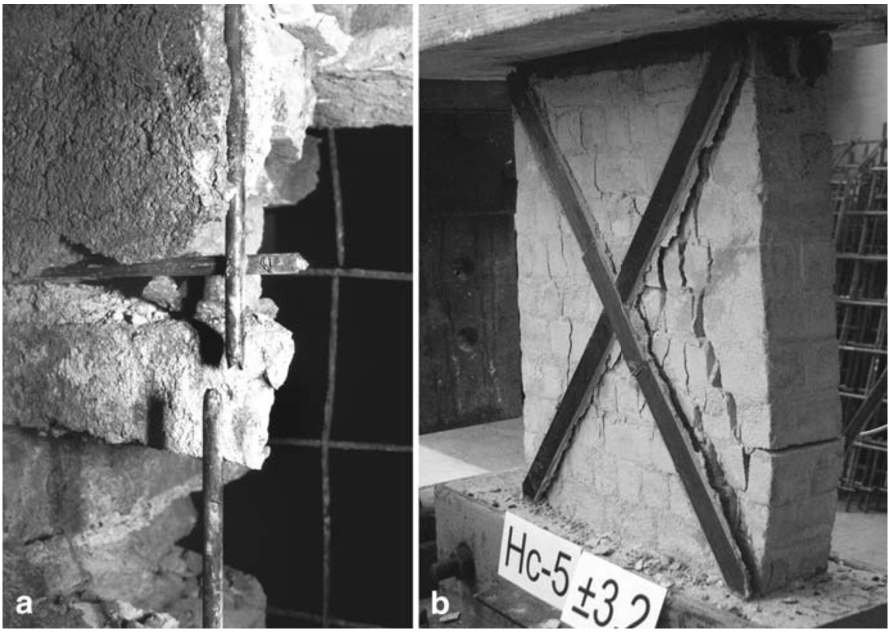

Fig. 17.5 Strengthening of brick-masonry walls by coating: **a** tensile rupture of reinforcing bar indicates the flexural failure mechanism of the strengthened wall and **b** delamination of diagonally placed CFRP laminate strips at shear failure

always so in the case of the application of CFRP coatings. Some results of tests carried out on masonry walls encourage the application, the others, however, showed up problems resulting from the bond and anchorage of CFRP strips glued on the walls' surface (Schwegler 1995; Triantafillou 2001). In other words, adequate solutions related to bonding and efficient interaction between the materials which have extremely different mechanical characteristics like CFRP laminates and masonry, are yet to be found. Wrapping the walls with CFRP mesh seems a better solution than glueing the diagonally placed strips. As is shown in Fig. 17.5b, CFRP laminate strips delaminate as soon as cracks develop in the walls. Failure occurs in the bricks and does not pass through the bonding material. Namely, because of the rigidity of CFRP laminate and the great difference in deformability characteristics between masonry and CFRP laminate (the modulus of elasticity of the laminate is a thousand times greater than the modulus of elasticity of masonry), the elongation of the laminate strips cannot follow the deformations of masonry in the non-linear range. Since the bonding material proved to be effective, the surface part of the bricks along the strips is pulled off.

Stone and mixed stone-and-brick masonry is most frequently characterised by two outer leaves of uncoursed stones (or uncoursed stones mixed with bricks) with an inner infill of smaller pieces of stones. Lime mortar, often of relatively poor quality, is used as a bonding material. Because of the way in which such walls are constructed, many voids, uniformly distributed over their entire volume, exist in the walls.

Therefore, systematically filling the voids by injecting cement-based grout is an obvious and efficient method of strengthening. The simple idea that, after hardening, the injected grout will bond the loose parts of the wall together into a solid structure, is followed. Although the use of cement-based grouting for the consolidation of engineering structures and soils has been known for almost 150 years (Miltiadou 1985), cement-based grouting was for the first time applied on a large scale to earthquake-damaged masonry buildings in Slovenia and Italy in 1976, after the earthquakes of Friuli. Since then, several studies have been carried out in order to investigate the possibility of various grout mixes being suitable for use in heritage masonry buildings. The idea of replacing the cement with inert aggregates and lime has been followed (e.g., Tomaževič and Apih 1993; Vintzileou and Tassios 1995; Vintzileou 2006). It has been found that the grout strength does not significantly influence the improvement in lateral resistance of the walls (Tomaževič and Apih 1993). Namely, a series of stone-masonry walls of the same type have been injected with different mixes of grout. Although the grout strength varied from 7–32 MPa, the shear resistance of the tested walls did not vary significantly. This makes possible the design of composition of the grout mix to meet the requirements of conservation and restoration of heritage buildings.

Since the results obtained by testing laboratory-built "original" walls are not always reliable because of the difficult reproduction of such walls, in situ lateral resistance tests are also carried out (Fig. 17.6a) to obtain reliable information regarding the degree of improving the lateral resistance (Tomaževič et al. 2000; Klemenc et al. 2000; Tomaževič and Petković 1997). As can be seen in Tables 17.1 and 17.2, where some indicative mean values of material properties are summarized, the

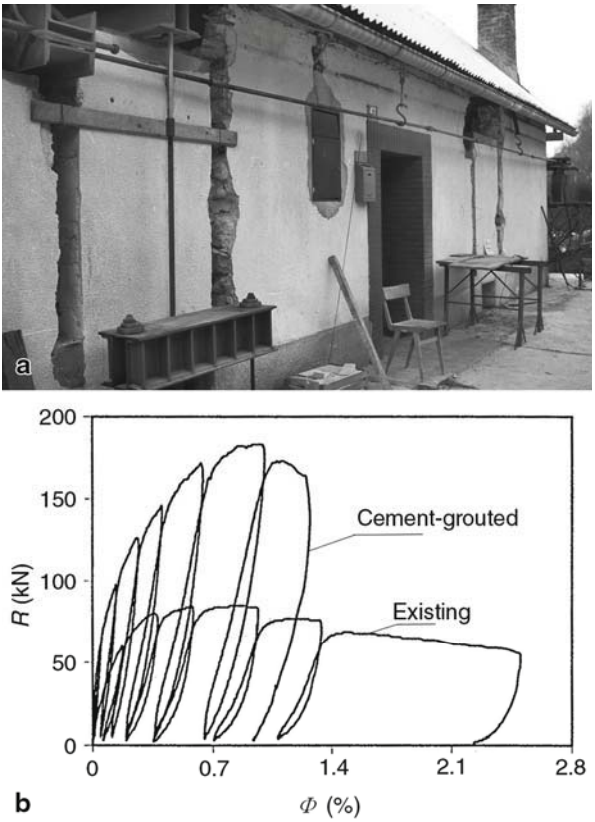

Fig. 17.6 Strengthening of stone-masonry walls with injections of cementitious grout. **a** In-situ lateral resistance test of walls in a typical rural house in Posočje Region and **b** typical effect of cement-grouting

Table 17.1 Mean values of compressive strength, *f*, and modulus of elasticity, *E*, of stone masonry in the existing (Exist.) in cement-grouted state (Inj.)

Type of wall	State	No. of tests	*f* (MPa)	Inj./Exist.	*E* (MPa)	Inj./Exist.
[a]Kozjansko:limestone; lime mortar with muddy sand non-homogeneous wall	Exist Inj.	2 1	0.51 0.97	1.9	1970 8250	4.2
[b]Montenegro:limestone; lime mortar with pure sand not plastered	Exist. Inj.	3 3	0.33 2.00	6.1	390 2610	6.7
[b]Montenegro:limestone; lime mortar with pure sand plastered	Exist. Inj.	2 2	0.77 2.33	3.1	3210 2940	~1.0
[c]Bovec: limestone; lime mortar with muddy sand; non-homogeneous; residential houses	Exist Inj.	1	0.98		2660	

[a] laboratory (Turnšek et al. 1978)
[b] laboratory (Tomaževič et al. 1980)
[c] in-situ (Klemenc et al. 2000)

Table 17.2 Mean values of tensile strength, f_t, and shear modulus, G, of stone masonry in the existing (Exist.) in cement-grouted state (Inj.)

Type of wall	State	No. of tests	f_t (MPa)	Inj./Exist.	G (MPa)	Inj./Exist.
[a]Kozansko: limestone; lime mortar with muddy sand non-homogeneous wall	Exist. Inj.	2 1	0.02 0.08	4.0	65 100	1.5
[b]Montenegro: limestone; lime mortar with pure sand plastered	Exist. Inj.	6 6	0.10 0.25	2.5	87 154	1.8
[c]Historic Ljubljana: mix of slate and limestone; lime mortar with muddy sand; relatively homogeneous	Exist. Inj.	1 1	0.13 0.20	1.5	40 350	8.8
[c]Historic Ljubljana: mix of slate, limestone and brick; lime mortar with muddy sand; relatively homogeneous	Exist. Inj.	1 1	0.15 0.17	1.1	40 550	13.8
[d]Friuli: mix of limestone and brick; good lime mortar with clean sand; homogeneous	Exist. Inj.	1 1	0.32 0.57	1.8		
[e]Bovec: imestone; lime mortar with muddy sand; non-homogeneous; residential houses	Exist. Inj.	1 1	0.06 0.11	1.8	80 170	2.1
[e]Bovec: limestone; lime mortar with muddy sand; non-homogeneous; public buildings	Exist. Inj.	2 2	0.08 0.20	2.5	170 400	2.4

[a] laboratory (Turnšek et al. 1978)
[b] laboratory (Tomaževič et al. 1980)
[c] in-situ test (Sheppard and Tomaževič 1986)
[d] in-situ test (Tomaževič and Petković 1997)
[e] in-situ test (Klemenc et al. 2000)

level of improvement depends on the quality of the original masonry. As can be seen, both the tensile strength and the rigidity of stone-masonry are increased after grouting. In the redesign, the increased rigidity of cement-grouted walls should be taken into account. A typical experimentally obtained correlation between the resistance curves of existing and cement-grouted wall is shown in Fig. 17.6b.

17.3.3 Design Seismic Loads and Damage Limitation Considerations

As a rule, the same level of seismic safety should be considered in the redesign of heritage buildings as in the case of a new construction. The structure should be designed to withstand an earthquake with a return period of 475 years and a 10% probability of occurrence within 50 years, "without local or global collapse, thus retaining its structural integrity and a residual load bearing capacity after the seismic events" (no collapse requirement, Eurocode 8 2003). However, the structure should also be designed to withstand an earthquake having a larger probability of occurrence than the design earthquake, i.e., earthquake with a return period of 95 years with a 10% probability of recurrence within 10 years, "without the occurrence of damage and limitation of use, the costs of which would be disproportionately high in comparison with the costs of the structure itself" (damage limitation requirement, Eurocode 8 2003). Seismic hazard maps have been prepared to provide basic information regarding the design earthquakes. Geotechnical data should be available to define possible soil amplification effects on the site. Microzonation, which provides more detailed data, is needed in specific cases.

According to Eurocodes 8 (2003, 2005), for all structural members as well as for the structure as a whole, the design resistance capacity, R_d, calculated by taking into account the characteristic strength values and partial safety factors, γ_M, of the members' materials, shall be greater than the design value of combined action effect, E_d, which includes seismic actions in the case where the structure is exposed to seismic hazard. Besides partial safety factors for materials, γ_M, used in the design of the new construction, confidence factors *CF*, which reflect the knowledge level of the actual materials' properties, are introduced in the seismic redesign of existing buildings.

In the case of structures with a regular structural configuration, design seismic loads are evaluated on the basis of the response spectra, considering the structure as an equivalent single-degree-of-freedom system. To obtain the design spectra, the ordinates of the elastic response spectra are reduced by structural behaviour factor *q*, which takes into account the energy dissipation and displacement (ductility) capacity of the structure as well as the damage limitation requirements. The design spectrum ordinate (design acceleration developed in the structure) is given as a fraction of the acceleration of gravity ($g = 9.81\ \mathrm{ms}^{-2}$) and is determined by:

$$S_{\mathrm{d}}(T) = \frac{a_{\mathrm{g}} S \eta 2.5}{q} \tag{17.1}$$

where a_g is the design ground acceleration at the site (in g), which is obtained from the seismic hazard map of the zone; *S* is the soil parameter, which is determined on the basis of the soil profile at the site; η is the damping correction factor, usually taken as $\eta = 1.0$; 2.5 is the spectral amplification factor for typical masonry structures; and *q* is the structural behaviour (force reduction) factor. According to Eurocode 8,

> the behaviour factor *q* is an approximation of the ratio of the seismic forces that the structure would experience if its response was completely elastic with 5% viscous damping, to the minimum seismic forces that may be used in the design—with a conventional elastic analysis model—still ensuring a satisfactory response of the structure.

Design seismic load (design base shear) is obtained by multiplying the design spectrum ordinate (acceleration) with the mass of the structure above the base ($m = W/g$):

$$BS_{\mathrm{d}} = S_{\mathrm{d}}(T) W/g \tag{17.2}$$

where *g* is the acceleration of gravity.

Analyses of earthquake damage observations and the substantial experimental studies which followed have improved our knowledge regarding the seismic behaviour of heritage buildings. Failure mechanisms have been defined and material characteristics determined which need to be taken into consideration when modelling the seismic behaviour of the structure under consideration and calculating the resistance of the structural elements. It has been found that different possible failure mechanisms should be taken into account and the critical ones considered in seismic resistance verification.

In a general way, the relationships between the lateral resistance, R, of the structure and displacements, d, are represented by the so called resistance curve. Usually, the displacements in terms of storey drift, d, are represented in a non-dimensional form of storey rotation, i.e., the ratio between the storey drift, d, and storey height, h, $\Phi = d/h$. A typical resistance curve is schematically presented in Fig. 17.7a, where the characteristic limit states that specify the behaviour of the structure are also defined. Before the attainment of the elastic limit (rotation $\Phi_e = d_e/h$), the structure is not damaged. The first cracks which change the stiffness but do not influence the usability of the building occur in the range between the elastic limit and the maximum resistance limit state, i.e., where the resistance attains the maximum value (in the range between Φ_e and $\Phi_{Rmax} = d_{Rmax}/h$), whereas the structure is still safe until the design ultimate state is attained (rotation $\Phi_u = d_u/h$). It is generally accepted that, regarding the no collapse criterion, rotation Φ_u, where the resistance degrades to 80% of the maximum, defines the ultimate design state of collapse. Although the experimental investigations indicate that the structure enters the actual state of collapse long after the deformations exceed the design ultimate state, the deformation capacity beyond this point is not taken into consideration because of the heavy damage which occurs to structural walls. To make the calculations simpler, the actual curve is sometimes idealized as bilinear, ideal elastic–ideal plastic relationship.

Shaking table tests of models of stone- and brick-masonry buildings (Tomaževič et al. 1993; Tomaževič et al. 1996) and in-situ and laboratory tests of existing and cement-grouted stone-masonry walls (Tomaževič et al. 1980, 1989; Klemenc et al. 2000) yielded the following ranges of values of rotation at limit states: $\Phi_e = 0.2–0.3\%$, $\Phi_{Rmax} = 0.4–0.5\%$, and $\Phi_u = 1.0–1.2\%$ (see also Fig. 17.7b). The values are slightly higher in the case of original walls than in the case of cement grouted, more rigid walls.

A recent study indicated (Tomaževič 2007) that in the case of the prevailing shear behaviour, typical for all masonry construction systems when subjected to seismic loads, damage grade 3 as defined by EMS-98 scale (European Macroseismic Scale 1998) can be defined as an adequate measure of damage limitation to be considered in the redesign. Grade 3 damage is defined as "moderate structural damage, cracks in many walls". At this level, increased number of cracks with limited width (less than 0.2 mm wide), oriented diagonally in both diagonal directions, develop in structural walls. It has been therefore recommended that in the redesign, displacement (ductility) capacity of masonry structures should not be utilized beyond the storey drift, equal to three times displacement (rotation) at the occurrence of the first cracks in the structural walls. Considering the resistance curve, the design

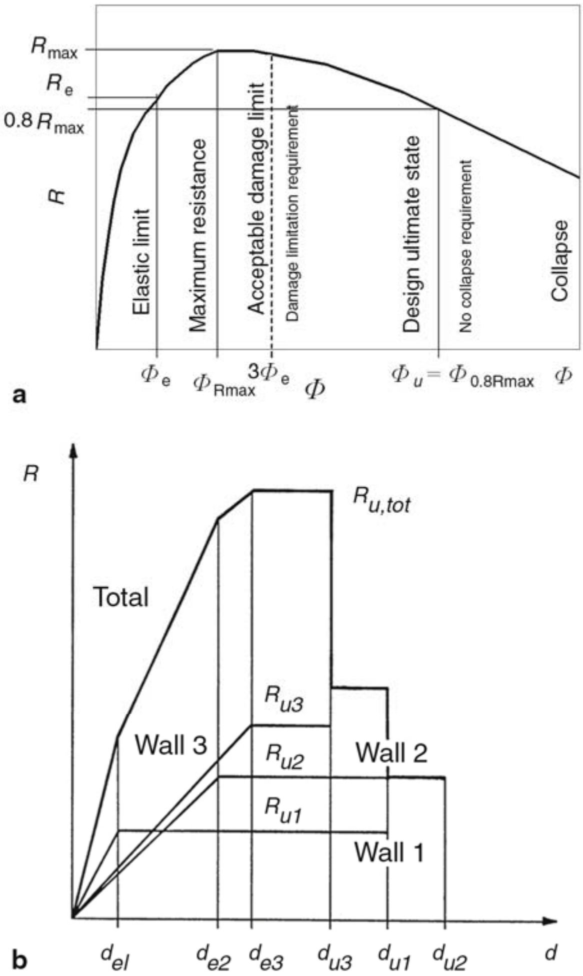

Fig. 17.7 **a** Resistance curve and definition of limit states and **b** superposition of idealised resistance curves of individual walls in the critical storey

ultimate state may be defined by either the displacement (rotation) value where the resistance degrades to 80% of the maximum, or the displacement (rotation) value, which attains three times the value of the displacement (rotation) at the idealized elastic limit, whichever is less:

$$\phi_{\mathrm{d,u}} = \min\{\phi_{0.8\,\mathrm{Rmax}}; 3\phi_{\mathrm{e}}\} \tag{17.3}$$

It is obvious that no collapse requirement governs the design in the case where the limit related with resistance degradation is critical, whereas the damage limitation requirement governs the design in the other case. Taking into consideration the smaller value of the two for the evaluation of the design parameters, such as behaviour factor q, both requirements will be fulfilled at the same time. In such a case there will be no need for the masonry structure to be checked for the serviceability limit state. Automatically, the seismic behaviour of the structure will be displacement controlled.

Based on the results of experiments and earthquake damage observations, and taking into account the damage limitation requirements, it has been proposed that the value of structural behaviour factor $q = 1.5$ be considered in the case where the non-linear, mechanism-based push-over type methods are used for the seismic resistance verification of heritage masonry buildings (Tomaževič 2007). Namely, if such methods are used in the redesign, and mechanical properties of masonry are determined by testing, little overstrength of the analysed structure is generally expected. In case the so assessed seismic resistance meets the design requirements and assuming that the measures to ensure the integrity of the masonry structure have been applied, adequate seismic behaviour of heritage buildings can be expected.

Usually, design seismic load is expressed in the non-dimensional form of the design base shear coefficient BSC_d, which is the ratio between the design base shear, BS_d, and the weight of the building, W: $BSC_d = BS_d/W$. Typical values of BSC_d, requested by Eurocode 8 for different expected seismicity of the site, are given in Table 17.3.

These values are relatively high. They can be easily attained in the case of a new construction of limited height, but they are sometimes difficult to attain if used in the redesign of heritage buildings, strengthened with ordinary strengthening technologies, particularly in the case of buildings higher than three stories. In many cases, it is practically impossible to attain the resistance required for the new construction without adding new structural elements. On the other hand, however, there have been many cases observed where the buildings resisted the earthquakes, although the calculated values of their design seismic resistance coefficient SRC_d (see Sect. 17.4) were lower than the BSC_d values required in the seismic zone. This justifies the idea that the design seismic loads may be reduced in either of two cases: (1) where the anticipated total cost of strengthening the entire building inventory of particular urban areas would sharply increase if design ground acceleration a_g values would be raised towards the code required level, or (2) if the code required

Table 17.3 Code design (BSC_d) and proposed reduced values of design base shear coefficient ($BSC_{d,r}$) for heritage masonry structures on firm soil ($S = 1.0$) and different design ground acceleration values (a_g)

a_g(g)	BSC_d	q	γ_r	$BSC_{d,r}$	$q_{\gamma n}$
0.05	0.08	1.5	1.00	0.08	1.5
0.10	0.17	1.5	1.00	0.17	1.5
0.15	0.25	1.5	0.92	0.23	1.6
0.20	0.33	1.5	0.83	0.28	1.8
0.25	0.42	1.5	0.75	0.31	2.0
0.30	0.50	1.5	0.67	0.33	2.3

γ_n – design seismic load reduction factor
q – structural behaviour factor (code value)
$q_{\gamma n}$ – structural behaviour factor (value corresponding to reduced design seismic load)

a_g values for redesign of a heritage building would lead to completely unacceptable architectural alterations.

As the analyses and observations after earthquakes indicate, the strengthening of heritage stone-masonry buildings in seismic-prone areas cannot be avoided. Whereas the tying of the walls should be provided in every case, experience shows that the strengthening of stone-masonry walls is needed in the zones of moderate and high seismicity, whereas in the zones of low seismicity, the decision whether the walls need to be strengthened or not, depends on the quality of the existing masonry.

Because of the structural configuration and specific characteristics of materials, neither partial solution nor adjustment of strengthening measures to individual levels of seismicity is reasonable. The existing stone-masonry building is either strengthened or not. Partial tying of the walls will not ensure the integrity of the structure. Similarly, partial grouting, aimed at adjusting the strength of the masonry to the required level of seismic loads, or at repairing the local damage, has little effect on the resistance of the structure. In all cases, however, the structural configuration of the building under consideration and the quality of the existing materials limit the level of seismic resistance attainable by these strengthening measures.

Taking this into consideration it has been proposed (Tomaževič 2000) that for practical redesign of heritage buildings a reduction factor $\gamma_n = 0.67$ be used in high seismic intensity zones ($a_g\ S = 0.30$ g), and no reduction, i.e., $\gamma_n = 1.00$, in the low intensity zones ($a_g\ S = 0.10$ g). The resulting proposed reduced values of the ultimate design base shear coefficient $BSC_{d,r}$ to be considered in the redesign of heritage buildings are also given in Table 17.2.

If explained in terms of damage, such a proposal implies that a slightly increased amount of damage to heritage buildings than in the case of a new construction be allowed for in the zones exposed to higher seismic hazard; however, this is still without risking collapse. If the proposal for the reduction of design seismic loads is explained in terms of damage limitation criteria, it can be seen that, instead of reduced a_g values, increased values of structural behaviour factor q may be used in the calculation of the design response spectrum ordinate according to Eq. 17.1. As can be seen in Table 17.2, where the resulting increased q factor values are also given, $q_{\gamma n}$, all values are within the range of values proposed by Eurocode 8 for plain masonry structures (q = 1.5–2.5). As the results of experimental studies indicate (Tomaževič et al. 1996), the expected displacement (ductility) capacity of heritage buildings, where structural integrity has been ensured by the tying of the walls, permits such a possibility without risking an excessive amount of damage.

17.4 Seismic Resistance of Heritage Buildings

In the case of the plain stone- and brick-masonry houses which fulfil the requirements for structural integrity, diagonal tension shear failure mechanism, characterized by diagonally oriented cracks in the walls (Fig. 17.2a), prevails and the shear resistance of the walls determines the seismic resistance of the building. Since the values of the shear modulus, G, of stone and brick-masonry are significantly smaller than the values of modulus of elasticity, E, the stiffness of individual walls is almost proportional to the area of horizontal cross-section of the wall. Consequently, negligible errors are made if the bending effects are neglected.

In the case of the diagonal tension shear failure mechanism, shear resistance of the wall can be calculated by equation (Turnšek and Čačovič 1971):

$$R_{\mathrm{d}} = A_{\mathrm{w}} \frac{f_{\mathrm{t}}}{b} \sqrt{\frac{\sigma_{\mathrm{o}}}{f_{\mathrm{t}}} + 1} \tag{17.4}$$

or similar expressions, where R_d is the design resistance of a wall; A_w is the area of the horizontal cross-section of the wall; f_t is the mean value of tensile strength; σ_o is the average compressive stress in the wall due to gravity loads; and b is a coefficient depending on the geometry and distribution of stresses in the critical section (usually, $b = 1.5$). In the case of the redesign and seismic assessment of existing buildings, the mean values of material strength, obtained by testing the existing materials, are reduced by confidence factor CF, which, according to Eurocode and depending on the amount of testing (knowledge level), varies between 1.00–1.35 (Eurocode 8 2005).

Past experience and recent studies indicate that a good correlation between the calculated results and the observed behaviour of heritage buildings can be obtained in the case where the resistance of the building is assessed by using shear mechanism models and average, unreduced values of material properties, obtained by tests, as input data in the calculations. However, it is proposed that, in the redesign, the requirements of Eurocode be slightly modified and the following recommendations regarding the values of confidence factor CF be considered in the assessment of seismic resistance of heritage buildings (Tomaževič 2000):

- $CF = 1.0$: mechanical properties of masonry are determined either by in-situ tests or in the laboratory by testing specimens taken from the building under consideration. At least one specimen of characteristic masonry should be tested in the building and the composition of the masonry should be verified by removing plaster at least in one location in each storey;
- $CF = 1.35$: mechanical properties are obtained by testing at least one specimen in the cluster of buildings of the same typology. Identification of a given type of stone-masonry is carried out by removing plaster and opening the walls at least in one location in each storey of the building under consideration;
- $CF = 1.7$: no testing. The values of mechanical properties are taken from the literature for masonry type, corresponding to the masonry type under consideration. Identification tests only are carried out.

There is no reason that, besides confidence factors, partial safety factors of materials, γ_M, be considered in the calculations as is required by Eurocode. For the purpose of redesign, the actual structural materials have been tested and the actual values of mechanical properties have been determined. Regarding the structural safety, there are no uncertainties regarding the values of mechanical properties of materials, required in the redesign, which depend on the factory control and inspection at the site in the case of the new construction. Moreover, as there has been no factory quality control and inspection on the construction site at the time of construction of heritage buildings, there is a question which value of γ_M to select.

Although stone-masonry is considered as brittle structural material, stone-masonry walls and structures possess substantial displacement and energy dissipation capacity. They are capable to carry the gravity loads even after being damaged by a strong earthquake and responding in the non-linear range of vibration. Therefore, when modelling the seismic behaviour of heritage buildings, displacement capacity in the non-linear range is attributed to masonry walls. The seismic loads are redistributed, which makes possible that the walls' lateral load bearing capacity be fully utilized. In the case of the shear mechanism, the seismic resistance of the building is determined by the lateral resistance of the critical, usually the lower-most storey of the building under consideration. The resistance is estimated by superposition of the lateral resistances of individual walls in the critical storey and taking into consideration the walls' displacement capacities (Fig. 17.7b).

A push-over type method has been developed for the calculation of the resistance curve of the critical storey. In the calculation, the displacements are imposed on the structure and the resisting forces of the structural walls are calculated. The stiffness and resistance of individual walls in each step of calculation are determined considering the imposed storey displacement and idealized resistance curves of the walls (Tomaževič and Turnšek 1982). Using this method, the seismic resistance of a series of heritage buildings in the existing and strengthened state has been analysed. To be compared with the design seismic loads, expressed in a non-dimensional form of the design base shear coefficient, BSC_d, the calculated values are also expressed in a non-dimensional form of the design seismic resistance coefficient, SRC_d, which is the ratio between the design resistance, R_d, and the weight of the building, W: $SRC_d = R_d/W$.

The seismic resistance of a number of stone-masonry buildings in Posočje (Soča River Valley), a mountainous region in the western part of Slovenia along the border with Italy, in the existing and strengthened state has been analysed after the earthquake of 1998 (typical examples of buildings are shown in Figs 17.1a and 17.6a). Material properties of stone-masonry walls in the existing and strengthened state have been determined by in-situ testing (Klemenc et al. 2000).

As can be seen in Table 17.4, where the results of calculations are summarized, the buildings in their existing state are expected to experience damage even when subjected to earthquakes of moderate intensity. The required values of the design base shear coefficient in the seismic zones where the design ground acceleration $a_g S = 0.15$ g and higher should be taken into consideration in most cases exceed the values of the available design resistance coefficient of buildings in the existing state (compare Table 17.3). The buildings in the existing state will experience heavy damage and even collapse when subjected to the strongest earthquakes, expected in the country. However, if strengthened by applying traditional strengthening meth-

Table 17.4 Seismic resistance of existing and strengthened heritage buildings in terms of design seismic resistance coefficient ($SRC_d = R_d/W$)

No.	Wall/floor area (%)		Existing			Strengthened		
	x-dir.	y-dir.	f_t (MPa)	$RC_{d,x}$	$RC_{d,y}$	f_t (MPa)	$RC_{d,x}$	$RC_{d,y}$
1	10.9	6.4	0.08	0.20	0.15	0.14	0.27	0.22
2	12.0	9.1	0.08	0.21	0.19	0.14	0.25	0.25
3	6.9	8.6	0.06	0.22	0.25	0.11	0.25	0.33
4	12.1	11.1	0.06	0.33	0.31	0.11	0.42	0.38
5	4.7	14.6	0.06	0.17	0.33	0.11	0.19	0.47
6	7.2	14.3	0.06	0.16	0.31	0.11	0.21	0.47
7	15.1	13.7	0.06	0.29	0.25	0.11	0.40	0.33
8	10.5	9.5	0.06	0.31	0.25	0.11	0.39	0.29
9	10.5	9.9	0.06	0.23	0.26	0.11	0.31	0.34
10	10.3	10.2	0.06	0.22	0.26	0.11	0.28	0.35
11	11.9	10.3	0.06	0.28	0.29	0.11	0.29	0.34
12	9.8	10.9	0.06	0.23	0.26	0.11	0.32	0.34
13	8.8	8.33	0.06	0.23	0.27	0.11	0.31	0.33
14	10.6	12.0	0.06	0.28	0.28	0.11	0.35	0.36
15	9.7	12.0	0.06	0.27	0.34	0.11	0.34	0.47
16	7.9	4.2	0.06	0.26	0.19	0.11	0.35	0.21

Note: f_t = mean tensile strength of masonry.

ods, such as cement-grouting and the tying of the walls, their resistance will be significantly improved. In the case of Slovenia, where maximum expected values of design ground acceleration do not exceed a_g = 0.25 g, the strengthened buildings, located on normal ground conditions (S = 1.0) will resist such earthquakes without collapse. However, depending on their height and foundation ground (S > 1.0), damage to structural walls of strengthened heritage buildings is in many cases unavoidable.

Not so frequently the same region suffered from three strong earthquakes in less than a 30 years time period. This, unfortunately, was the case of Posočje, which in 1976 suffered from a series of earthquakes with epicentres in nearby Friuli, and then again in 1998 and 2004 from two local earthquakes with epicentres near the town of Bovec. Although the earthquakes of 1998 and 2004 cannot be compared with Friuli earthquakes of 1976 by magnitudes, their maximum local intensities, estimated at VIII on the EMS seismic intensity scale (Tomaževič et al. 2005) were similar. There have been earthquake acceleration records obtained of the main shocks of September 1976 and July 2004 earthquakes, but no records exist of the earthquake of April 1998. Peak ground acceleration values of 0.53 g and 0.47 g have been recorded in 1976 (in Breginj) and 2004 (in Bovec), respectively, though not on the same location.

According to the seismic hazard map of Slovenia, design acceleration value a_g = 0.225 g should be considered in the area, and BSC_d = 0.375 should be considered in the design. If this value is reduced as proposed (Table 17.3), the reduced design base shear coefficient $BSC_{d,r}$ = 0.30 should be considered in the redesign of heritage buildings. In other words, the design seismic resistance coefficient of the strengthened heritage buildings in the area should be at least $SRC_{d,r}$ = 0.30 when the buildings are located on firm ground (S = 1.0). Most of the buildings, analysed in

Table 17.4, located in the area, would meet this demand. Some, however, cannot be strengthened to the required degree by using traditional methods. Other techniques to meet the demands should be used in these particular cases.

The results of seismic resistance analysis, summarized in Table 17.4, have been verified by taking advantage of ground acceleration records obtained in 2004. Several buildings, strengthened after 1998 but damaged again in 2004, located near enough to the site where the records have been obtained, have been analysed. Although a simple, equivalent single-degree-of-freedom model has been used, the analysis provided a realistic simulation of what happened on July 12, 2004. The buildings have been modelled as simple planar multi degree of freedom shear systems, with masses concentrated at floor levels and storey stiffnesses. Hysteretic behaviour has been modelled by a set of rules, which take into consideration strength and stiffness degradation and deterioration at repeated load reversals (Tomaževič and Lutman 1996). The calculated storey shear-rotation hysteresis loops of a typical analysed building are presented in Fig. 17.8a. For comparison, the observed damage to structural walls of the same buildings after the earthquake of July, 2004, is shown in Fig. 17.8b.

It can be seen that the dynamic response of the analysed buildings to earthquake ground motion entered into the non-linear range of vibration. In other words, the occurrence of damage to structural walls during an earthquake as strong as the earthquake of July 12, 2004, could have been expected, although the building had been previously strengthened by tying and cement grouting of stone-masonry walls. The response analysis has also shown that, in the particular case studied, the calculations simulated the occurrence of cracks in both the ground floor and first storey as has been actually observed after the earthquake (see Fig. 17.8b). The calculated values of storey rotation are well within the range of values, determined as characteristic for the limit states of maximum resistance $\Phi_{Rmax} = 0.4–0.5\%$, and design ultimate state $\Phi_u = 1.0–1.2\%$. Good agreement between the observed damage and the results of calculation confirms the validity of the method, used for seismic resistance verification of regular heritage masonry buildings.

During the earthquake of July 2004 significantly higher values of peak ground accelerations have been recorded ($a_{gmax} = 0.47$ g) than expected according to the seismic hazard map ($a_g = 0.225$ g). However, the expected design and maximum recorded values cannot be directly compared. Ground accelerations have been recorded on river gravel deposits of considerable depth. As indicated by a backward analysis (Fajfar et al. 2004), the measured peak values on the ground would correspond to peak values of bed-rock accelerations between 0.16 g and 0.23 g. This means that the intensity of the earthquake of July 2004 in the most affected area was equal to or even higher than the intensity of the design earthquake for the area of Bovec.

The study indicated that technical solutions are available to reduce the seismic risk of most heritage masonry buildings in urban and rural settlements in Slovenia to an acceptable level. By applying these measures to buildings, the collapse during the expected design earthquakes will be prevented; however, depending on the buildings' height and foundation ground, damage may occur to structural walls. In

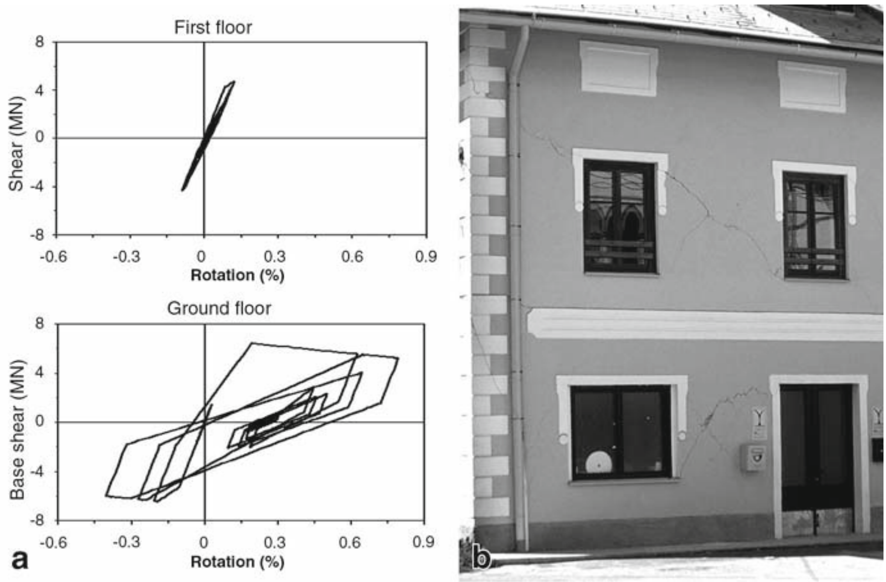

Fig. 17.8 **a** Hysteretic response of the first and second floor of the analysed building to N-S component of July 12, 2004 earthquake ground acceleration record and **b** damage patterns observed in the walls of the analysed building after the earthquake

a way, this has already been confirmed in the Posočje Region in 1998, where there have been cases of disintegration and partial collapse of individual walls observed in the case of buildings not adequately strengthened after the earthquakes of 1976. However, in no case did a building collapse totally.

17.5 Conclusions

Extensive and coordinated experimental research over the last few decades has made possible an improvement in technologies for the reduction of seismic risk of heritage masonry buildings in urban and rural settlements. On the basis of the analysis of earthquake damage, experimental investigations in seismic behaviour of masonry walls and buildings, as well as tests for the determination of mechanical properties of existing masonry materials and the efficiency of strengthening measures, methods and recommendations for seismic assessment and retrofit have been developed. On the basis of the results of experimental and analytical research, contemporary methods for the assessment of seismic resistance of existing masonry structures have also been proposed.

It has been shown that, by correctly applying these methods to heritage buildings, the no collapse criterion, as required by contemporary seismic codes and standards, will be fulfilled in seismic-prone zones in Slovenia. As regards damage limitation criteria, however, an increased amount of damage to structural walls may be expected in specific cases, depending on the height of the buildings and foundation ground, but without risking total collapse.

In order to protect our architectural cultural heritage from seismic risk, systematic seismic rehabilitation campaigns are needed. However, although technical knowledge exists and economical and efficient technologies have already been developed and verified, technologies which are acceptable from the point of view of the preservation and conservation of our architectural cultural heritage, actions are few. Although earthquakes occur rather frequently, the level of public awareness is still low. Even in the case of costly reconstruction after damaging earthquakes, people often do not bear in mind the likelihood that earthquakes will strike again in the future.

Acknowledgements This paper has been prepared on the basis of the results of research that the author and his colleagues have carried out and published over the last decade. The reader may find more detailed information in the referenced publications.

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Chapter 18
Acoustic Emission Monitoring of the Cathedral of Palma de Mallorca (Spain)

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18.1 Introduction

18.1.1 Fractures in Masonry

The presence of fractures and fissures in a building is the consequence of an inadequate response of its structure and/or materials to the stresses affecting them. Frequently, primarily in large buildings, the soil-structure interaction modifies the distribution of stress on the structure: differential settlement, unforeseen strains, underground instability, etc. are some of the causes that can induce fractures in the structure or in building materials. Generally speaking, the fractures and fissures caused by these factors cease to grow after a short time and do not represent a problem for the building's stability.

At other times, the degradation and deterioration of the building stone that occur naturally (due to rain, wind, freezing–thawing, thermal variations, soluble salts, etc.) and are caused by human activity (due to atmospheric pollutants and contaminants such as gases, smoke, soot, etc.) greatly decrease their mechanical characteristics, on occasion creating cracks capable of ruining the building.

Other natural causes that can affect soil and/or structure, may also give rise to structural damage. In this sense, the movements of the material and structure due to thermal variations cannot be underestimated since the generated stresses may lead to failure. Similarly, variations in the relative humidity of the masonry elements and of the building underground can induce cyclic, usually seasonal movements, with the same effects as those mentioned above. Lastly, and more specifically in the present case, the action of seismic movements of greater or

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lesser intensity can lead to momentary mainly horizontal stresses that are capable of damaging the building structure as well as permanently displacing one part with respect to another.

18.1.2 Aims of the Study

The aim of this paper is to determine the present state of damage of the Cathedral of Palma de Mallorca (Fig. 18.1) by means of fracture studies. Thus, with future studies it will be possible to follow the time dependent development of fractures of the Cathedral. At the same time, the spatial distribution and orientation of these fractures may help to establish their possible causes and aid in planning the appropriate repair works.

The crack pattern studies of the structure have been performed by visually inspecting its elements (walls, buttresses, flying buttresses, columns, etc.). The fractures caused by shear stresses were also noted, as was the deformation of walls, since these may prove to be dangerous. The fractures have been mapped on the prospect maps of the Cathedral to identify their origin and the location of the most highly damaged zones. Some examples of the fractures encountered in the Cathedral can be found in Fig. 18.2.

Fig. 18.1 View of the Cathedral of Palma de Mallorca (S. and E. façades)

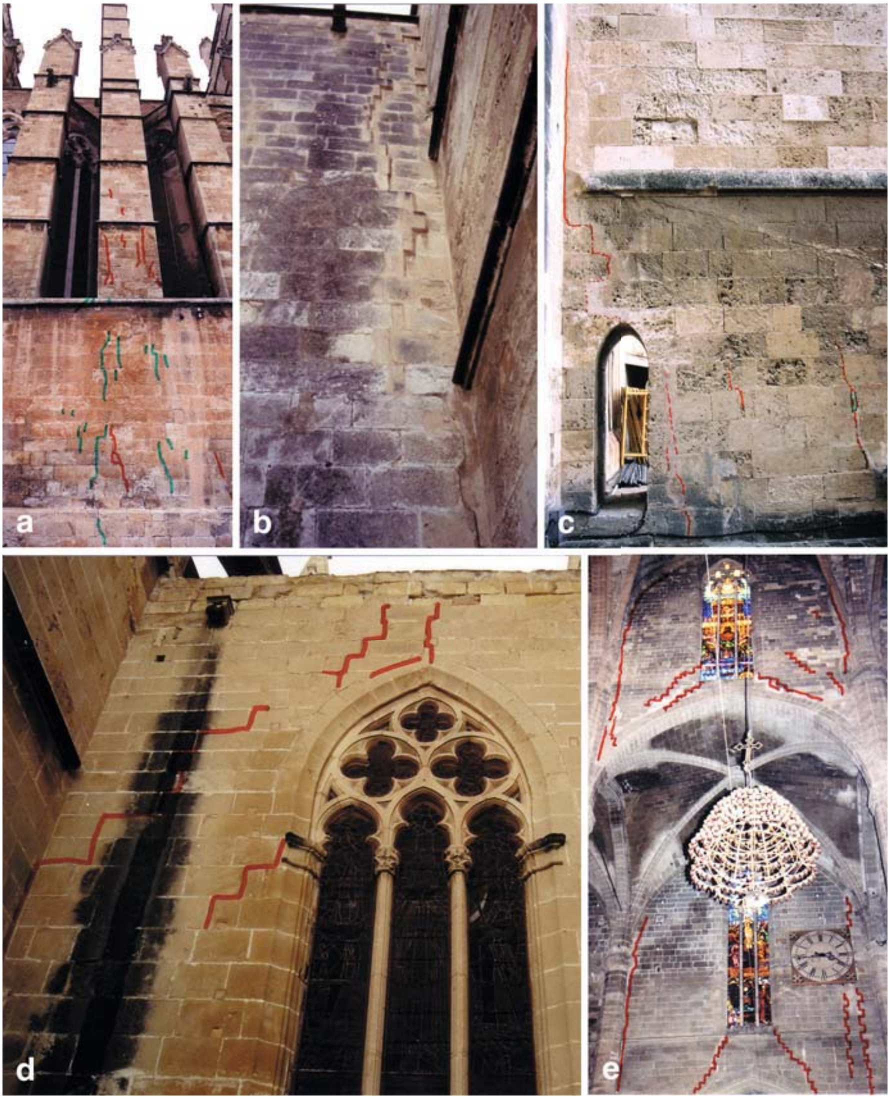

Fig. 18.2 Fractures of different origin at the Cathedral: **a** due to overloading, at the bottom of a buttress, **b** fracture with shear displacement, due to the 1851 earthquake, **c** fractures due to underground settlement, in this case, due to the central nave settlement, located at the *left* of the picture, **d** fractures due to deformation of the large windows, **e** idem, view from the inside of the Cathedral

18.1.3 Types of Fractures

It should be stated that the classical division of "fissures" (cracks of less than 1 mm thick) and fractures (cracks thicker than 1 mm) has not been adhered to in this paper

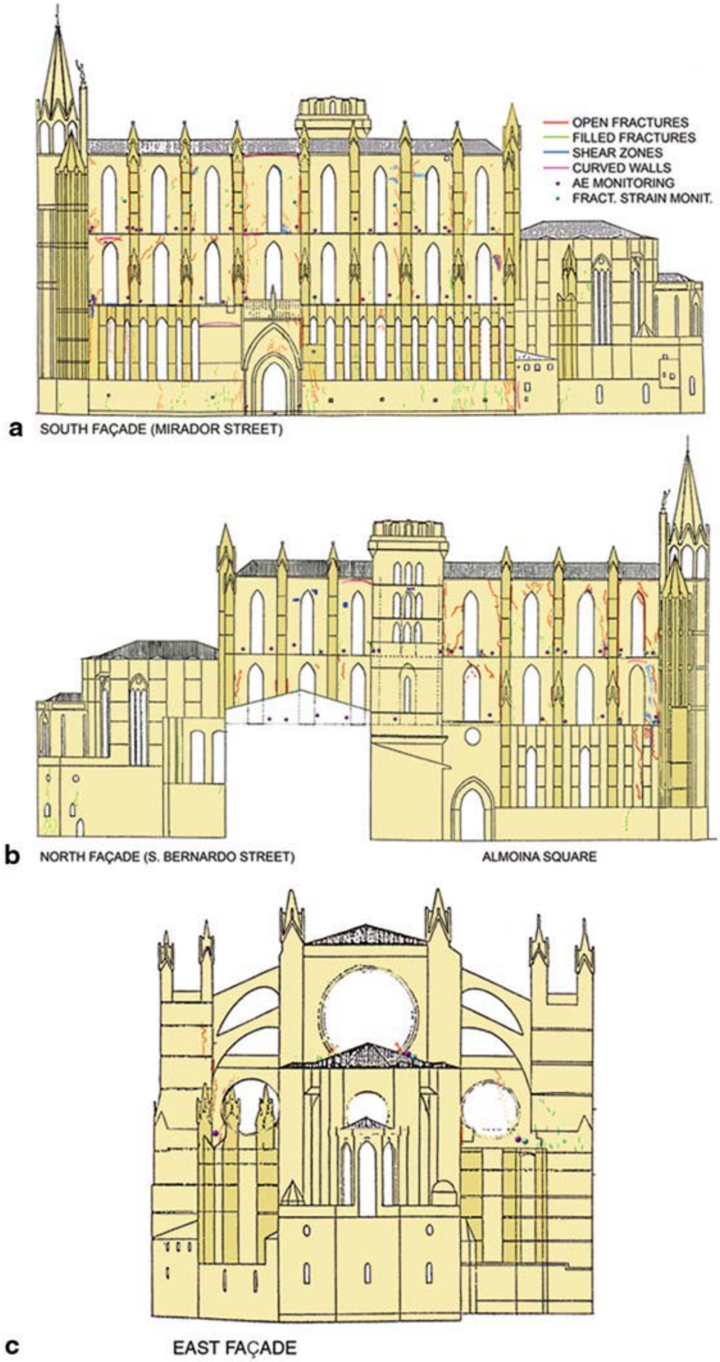

Fig. 18.3 Prospect map of fractures on: **a** south, **b** north, and **c** east sides of the Cathedral

since the thickness in some of them changes along the discontinuity and, in some cases, the fissures and fractures were sealed with mortar and their thickness is not easily observed. Hence, we have referred to all of them as "fractures". However, whenever possible, the fractures have been classified into two categories: "open fractures", generally the most important ones with no natural material filling them, and "filled fractures", the ones that are filled, ordinarily by dust that is to a greater or lesser degree consolidated, or by soluble salts. The latter can be considered as "dead fractures" in that their dimensions have stabilized with time. The location of the most important fractures is shown on the prospect maps of the Cathedral (Fig. 18.3).

Open fractures are present in all the walls of the Cathedral, although they are more numerous in the western part of the building, where they have even separated the towers from the central nave.

18.2 Changes in Fracture Openings

Forty-four plaster witnesses have been located in a number of these open fractures, some in excess of 1 cm thick, and after 7 months, 17 of them had broken. Most of these broken witnesses were in the western central part of the Cathedral. The movements (opening and closing) of 14 open fractures, most coinciding with those in which the witnesses were broken (cf. Fig. 18.3), have been monitored using mechanical displacement gauges (1 μm resolution) during the daytime (Fig. 18.4). The surface temperature of the stone near the monitored fracture has also been measured.

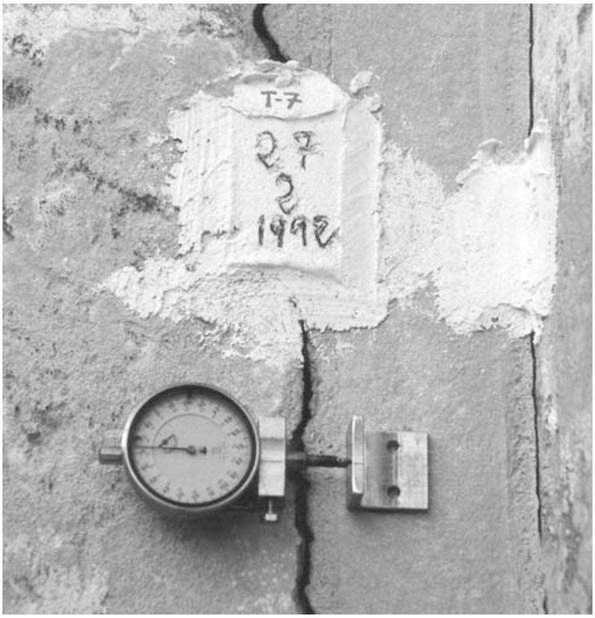

Fig. 18.4 Mechanical gauge for measuring fracture movements

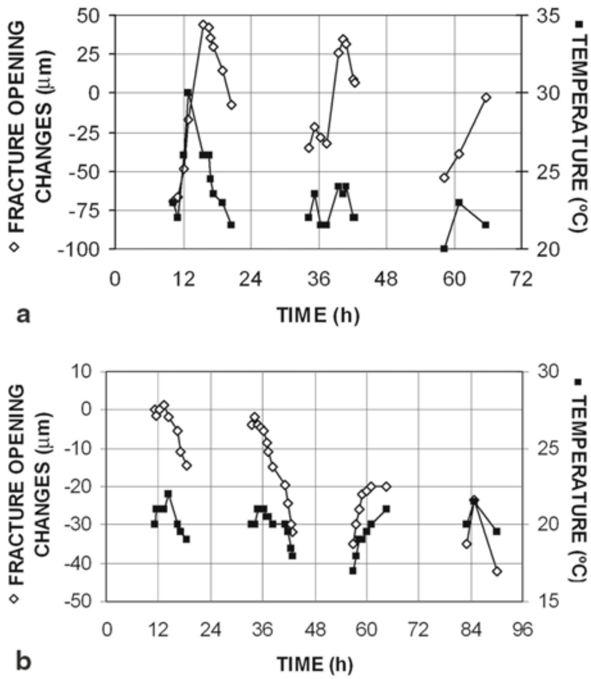

Fig. 18.5 Displacements in a fracture located on: **a** south façade maximum displacement: 131 µm; timepoints 0, 24, 48, and 72 correspond to midnight; timepoints 12, 36, and 60 to midday, **b** north façade maximum displacement: 43 µm; timepoints 0, 24, 48, 72, and 96 correspond to midnight; timepoints 12, 36, 60, and 84 to midday

The first conclusion that can be drawn from the monitored movements is that greater displacement of the fracture walls takes place on the south façade. In some cases, the relative displacement of the fracture walls exceeds 200 µm and might possibly be found to reach 300 µm if the movement data pertaining to nocturnal displacements were also available.

These movements have been attributed to the thermal expansion of the walls, since there has been a close correlation between environmental temperature and displacements (Fig. 18.5). The fissures in the plaster witnesses can be attributed to the same origin. The plaster witnesses were put in place in February, when the temperature in Palma de Mallorca is mild, and inspected in September, in late summer, when temperatures were higher and the displacements on the fracture walls were also greater.

18.3 Rock Building Materials

The Cathedral was built with four types of carbonate rock from the Miocene (Alonso et al. 1996). The main structure of the Cathedral is of white dolomite and white limestone. A grained limestone was used to close up some large windows, while oolitic limestone was used at the main entrances (west and south façades), where it was sculpted and engraved. In this paper we have retained the rock names used in the paper of Alonso et al. (1996), where their petrographical characteristics as well as

Table 18.1 Petrographical characteristics of the four types of stone of the Cathedral

Rock type	Mineralogical composition (%)			Rock fabric characteristics		Mineralogical classification	Textural classification (Dunham 1962)
	Calcite	Dolomite	Quartz	Components	Size		
White dolomite	2	94	4	Grains: red algae Crystals: dolomite	mm 20 µm	Dolomite	Crystalline dolomite
White limestone	83	17	–	Grains: bioclasts Matrix: micrite	mm < 4 µm	Dolomitic Limestone	Mudstone-Wackestone
Grained limestone	95	5	–	Grains: calcite Cement: very scarce	250 µm	Limestone	Grainstone
Oolitic limestone	100	–	–	Grains: oolites Cement: sparite	750 µm 100 µm	Limestone	Grainstone

Table 18.2 Petrophysical characteristics of the four types of stone of the Cathedral

Rock type	Open porosity (vol.%)	Macroporosity (r > 7.5 µm) (%)	Microporosity (r < 7.5 µm) (%)	Pore radius (µm)
White dolomite	45.6	27.4	18.2	12
White limestone	40.3	4.8	35.5	3
Grained limestone	36.2	32.6	3.6	40
Oolitic limestone	27.8	4.2	23.6	0.06

some of their petrophysical properties can be found. They are summarized in Tables 18.1 and 18.2; the textural classification following Dunham (1962) has been added.

18.4 Acoustic Emission

18.4.1 Laboratory Tests

Before monitoring acoustic emission at the Cathedral, the acoustic emission profile of the "intact rock" of the ashlar stones when subjected to stresses must be known, since the acoustic emission profile can differ depending upon the material tested. Some rocks have a high acoustic emission rate from the beginning of the loading process, while others exhibit almost no activity whatsoever until a high percentage of their ultimate strength is reached (Montoto et al. 1981, 1984). This means that an acoustic emission rate can be assigned to a settlement of the rock voids at low loads or to a fracture process at high loads, near the point of collapse.

Three of the four types of stone of the Cathedral of Palma de Mallorca have been tested under uniaxial compressive and bending stresses. The oolitic limestone was not tested since it was only used for the sculptures at the main entrances of the Cathedral. From the other three types of stone which the Cathedral is made of (white dolomite, white limestone, and grained limestone), a minimum of four, square-based, prismatic specimens have been obtained for each of the programmed compression and bending tests.

For the uniaxial compression tests, the specimens were 10 cm long by 5 cm base edge. Prior to testing, they were dried at 60°C for at least 48 h. The loading rate was 350 N s^{-1}, lower than ASTM recommendations (1987), since stress changes at the Cathedral must be induced very slowly. Longitudinal strain was monitored by electrical strain gauges. The acoustic emission rate during loading (in compression as well as in bending tests) was monitored with an AET 240 GR device; gain was 92 dB, and the monitored bandwidth 100–300 kHz.

Figure 18.6 displays the stress-strain curves as well as the trend of the acoustic emission profile recorded during loading for the three types of stone tested. It is evident that the strength is low for all the stones (between 6 and 12 MPa), as is Young's modulus (between 6 and 17 GPa). The trends of the acoustic emission rate correspond to those of highly porous stones, with a significant initial AE rate, due to the collapse of voids or to fissure closing during the initial loading steps, followed by a decrease during elastic behaviour. The AE rate increases when cracking begins and becomes greater as the specimen approaches collapse (Montoto et al.1981, 1984). On the basis of these figures, the acoustic emission rate of the white limestone is seen to be very low in comparison with the other two types of stone (note that the AE rates in Fig. 18.6a, c are multiplied by 1000 and in Fig. 18.6b by 10).

In the three-point bending tests conducted, the specimens were also prismatic (300 × 50 × 50 mm). A loading rate of 20 N s^{-1} was used; the distance between supporting rods was 25 cm and the loading rod was located in the middle. Specimen drying was similar to that employed in compression.

Figure 18.7 presents the results during the bending tests performed on the three types of stone. The bending strength was so low that it was not taken into consideration in the figures; and load was represented as a percentage of the maximum load. The acoustic emission rate was expressed in counts per 0.5 s for all the stones.

As in the compression tests, the white limestone shows a much lower AE rate than the white dolomite and grained limestone. The AE rate in the white limestone is negligible throughout the entire loading process and only increases at the rupture point.

As a conclusion of the mechanical tests carried out, white limestone can be said to generate a low AE rate, unlike the other stones tested. This may be due to different causes that could act individually or in combination, for example:

a) The acoustic emission generated in the white limestone is in a different frequency range from that registered by the transducer (100–300 kHz).
b) The acoustic emission has very low energy and the waves might be dampened prior to reaching the transducer.
c) The background noise threshold during AE monitoring was too high for this kind of stone.

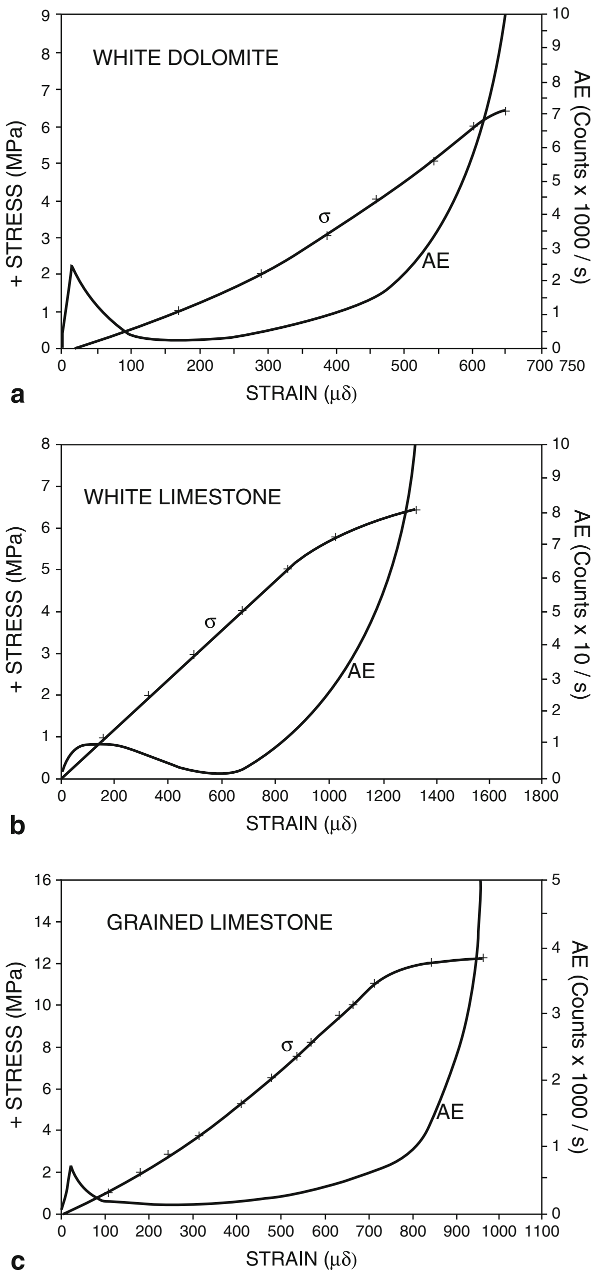

Fig. 18.6 Stress-strain curves and AE rate trend during uniaxial compressive test for: **a** white dolomite, **b** white limestone, **c** grained limestone. Note that the AE scale in Figs. 18.6 and 18.8 is multiplied by 1000 and by 10 in Fig. 18.7

In order to increase the possibilities of recording the acoustic emission in this kind of stone at the Cathedral, the AE rate time unit used for in situ testing was increased to 10 s instead of the 1 and 0.5 s used in the laboratory.

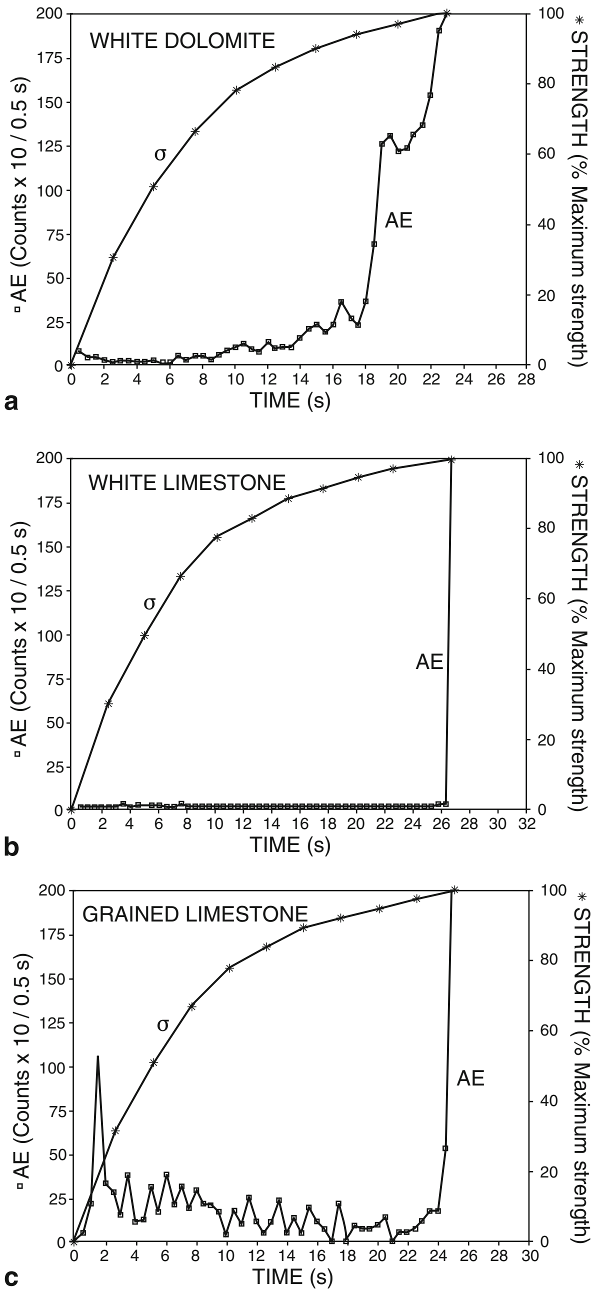

Fig. 18.7 AE rate and stress variation percentage of the maximum strength with time during bending test for: **a** white dolomite; **b** white limestone; **c** grained limestone

18.4.2 In-Situ Measurements

Although the AE technique has been used in rocks (underground structures, mines, slopes, etc.), not many papers have been published that deal with its applications to buildings. Among the first papers to appear in the literature, Caneva and Maravelli (1983); Mazurek (1984); Leaird (1984); and Goszcz and Kotyrba (1988) have studied the possibilities of using AE techniques to obtain information on structural changes of materials in buildings. Later, Montoto et al. (1995) reported a review of the application of the technique in stone conservation. In the last few years, Shigeishi (2001); Shigeishi et al. (2001); Carpinteri and Lacidogna (2001, 2003, 2006); and Carpinteri et al. (2007) have described the application of AE techniques to monitoring concrete and masonry buildings in order to determine the stability conditions or risk resulting from defect spreading.

This monitoring of acoustic emission at the Cathedral of Palma de Mallorca has been performed using Acoustic Emission Technology AET 240 GR and Physical Acoustic Corporation PAC Spartan 3000 equipment, with a transducer frequency range of 100–300 kHz. There was a gain of 82–92 dB (AET) and 60 dB (PAC) (plus 40 dB of the preamp). Transducers were fixed to the walls with elastic bands and a coupling agent made of special grease added to the base of the transducer so as to enhance reception of the AE signals. To reduce vibrations produced by the wind, the AE transducers were covered with a plastic protector (Fig. 18.8).

Acoustic emission was monitored in 77 areas (see Fig. 18.3 for location; however, two areas inside the Cathedral and one on the west façade have not been represented). Transducers were located on the stone walls, buttresses, flying buttresses, and even on the plaster witnesses. Each area was monitored for a minimum of 3 h, although in some cases, monitoring was carried out for 14 h or more.

In Figs. 18.9, 18.10, and 18.11, the AE rate is presented for two zones of the Cathedral, on the N and S façades. AE in Figs. 18.9 and 18.10 was recorded with the PAC equipment; AE in Fig. 18.11 was recorded using the AET equipment.

In Fig. 18.9, some intermittent AE peaks appear, corresponding to the chimes of the Cathedral clock which ring every 15 min; we can consider them as "cultural noise". The chimes do not ring from 9 p.m. until 7 a.m. The different heights of

Fig. 18.8 Transducer protection system during AE monitoring

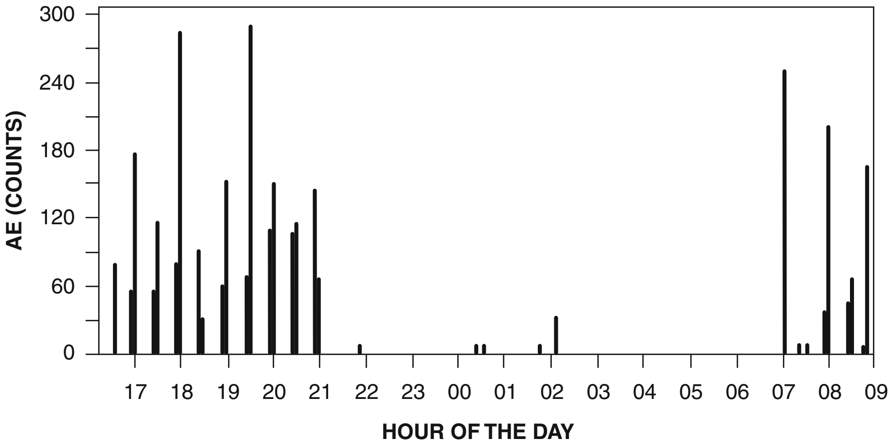

Fig. 18.9 AE rate between 4 p.m. and 9 a.m. on the north façade (PAC equipment)

the peaks due to chimes mainly depended on the wind direction: when the wind was blowing towards the transducer (higher sounds), higher peaks were recorded. On the other hand, the duration of the chimes could have affected the peak height: shorter duration, smaller peaks; even the duration of the chimes, could take a portion of one or more 10 s periods (the time unit used to measure the AE rate), affecting the peak height: for example, at 5 p.m., the 5 chimes could be monitored in a single 10 s period (higher peaks) or split between two 10 s periods (e.g., 2 chimes belonging to the first and three more to the second), thus resulting in smaller peaks.

Other AE counts of lower intensity have been monitored between the peaks due to the chimes. In Fig. 18.10, a portion of Fig. 18.9 has been represented (from around 4 p.m. until 9 p.m.). Here, the lower intensity peaks are more readily dis-

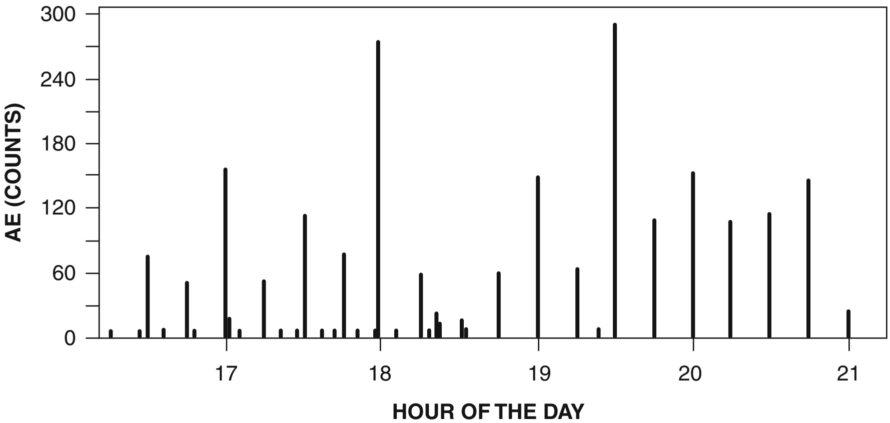

Fig. 18.10 AE rate of the first 5 h of Fig. 18.9

cerned. They can reach a maximum of 20–30 counts per 10 s. From 6 p.m. onward, almost no AE was monitored. The peaks that appear between about 0.30 and 2.15 in Fig. 18.9 are due to light rain.

The AE due to the chimes are particularly noticeable in Fig. 18.11, although other AE counts can also be seen between the peaks. Their AE rate tends to be less than 20 counts per 10 s.

The acoustic emission monitored could be partially accounted for by "cultural noise" (the Cathedral clock chimes or even drops of rain during showers), the highest peaks being produced in the acoustic emissions monitored.

The other AE events could be attributed to other causes, for example, to other kinds of "cultural noise" such as the noise produced by vehicles circulating near the Cathedral, but this idea must be rejected since three or four transducers located in the same area, 1–3 m apart, were monitoring the AE and most of them should have registered this same cultural noise, but this was not the case. The AE events monitored by one transducer were different to those of the others. This also means that the monitored AE was generated in an area near the transducer since the propagation of the AE wave did not reach the other transducers due to damping. This is another reason for rejecting the idea that the AE was due to soil settlement or overloading. Moreover, the AE rate was not higher in the lower part of the Cathedral (where overloading and settlements could be more intense) and the AE rate was, in fact, much lower during the AE monitoring process inside the temple, where the temperature variations are not very significant.

In view of this, we believe that most of the AE events not linked to the clock chimes are the result of the thermal expansion of the building's stone ashlars, with lower AE peaks, since these peaks are more abundant during the sunnier hours of the day and on the south façade. At night, almost no acoustic emission was monitored.

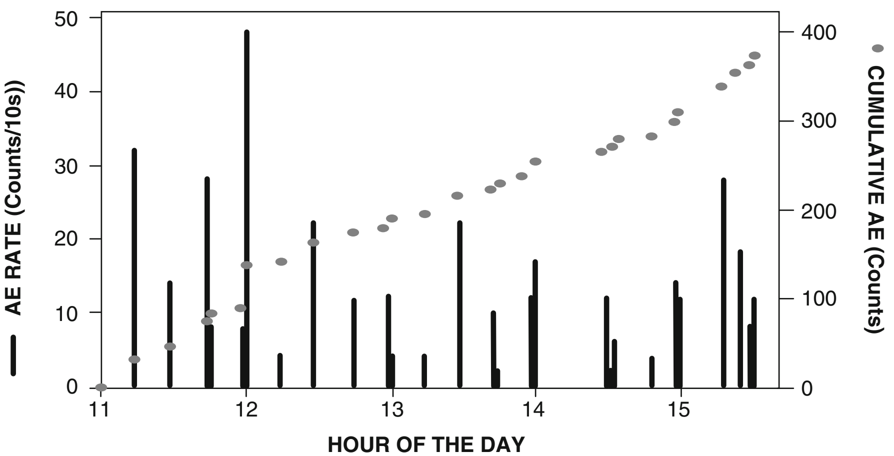

Fig. 18.11 AE rate and cumulative AE between 11 a.m. and 4 p.m. on the south façade (AET equipment)

However, AE monitoring during much longer periods of time is probably needed in order to assess this assertion.

18.5 Conclusions

The Cathedral of Palma de Mallorca has fissures and fractures due to ground settlement (chiefly underneath the central nave), overloading (mainly at the lower part of the buttresses), deformation of the large windows and an earthquake in the 19th century. Open fractures are present in all the walls of the Cathedral, although they are more numerous in the western part of the building, where the towers have even become separated from the central nave by open fractures.

The variations in fracture opening, as much as 250 μm, may be related to the thermal expansion of the stones that the Cathedral is made of. A close correlation between the environmental temperature and changes in the fracture opening has been determined.

Three of the main types of stone used to build the Cathedral have been tested under uniaxial compressive stresses and bending stresses. The mechanical strength was very low for all three types and the acoustic emission trend monitored during compression tests was that expected for high porosity rocks; however, the AE profile of the white limestone was much lower than the white dolomite and grained limestone. The white limestone also exhibited a lower AE rate during bending tests and the significant AE appears just before collapse.

The acoustic emission profile at the Cathedral is low and is higher during the day and on the sunnier south façade; at night the monitored acoustic emission was almost zero. The monitored AE events may be associated with "cultural noise" (Cathedral clock chimes and rain showers) and with the thermal expansion of the stone ashlars that produces the changes in the openings of the fractures, although longer AE monitoring periods are probably needed to assess this last statement.

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