Permeable Interlocking Concrete Pavements

Selection • Design • Construction • Maintenance

David R. Smith

Third Edition

ICPI
INTERLOCKING CONCRETE
PAVEMENT INSTITUTE ®

Permeable Interlocking Concrete Pavements

Selection • Design • Construction • Maintenance

David R. Smith

ICPI
INTERLOCKING CONCRETE PAVEMENT INSTITUTE ®

1444 I Street NW–Suite 700
Washington, DC 20005-6542
Tel: 202-712-9036
Fax: 202-408-0285
E-mail: ICPI@icpi.org
Web: www.icpi.org

In Canada
P.O. Box 85040, 561 Brant Street
Burlington, ON L7R 4K2

Third Edition 2006

Contents

continued next page

Contents *continued*

List of Figures

continued next page

List of Figures *continued*

Acknowledgements

Taking a project from idea to reality often takes longer than anticipated. This manual is an example. It was proposed to the Technical Committee of the Interlocking Concrete Pavement Institute in the early 1990s. The idea was well-received, but other priorities placed the project on the sidelines. Postponements, however, are often a blessing in disguise. More time was provided for research and for literature to be reviewed.

Thanks goes to the Technical Committee and the Board of Directors of the Interlocking Concrete Pavement Institute for providing me the time and funding to create this manual. Deb Stover of Image Media created the drawings and formatted this publication. Thanks is due to Tom Schueler, from the Center for Watershed Protection in Ellicott City, Maryland. His practical insights and experience with best management practices for abating water pollution, plus the library at his Center were invaluable to bringing this manual into reality.

My thanks and appreciation are due to several others for their review of the text:

Raymond S. Rollings, Ph.D., P.E. U.S. Army Corps of Engineers
Waterways Experiment Station, Vicksburg, Mississippi

Joeseph Batiatta, Program Manager, Stormwater Management
Virginia Department of Conservation and Recreation,
Richmond, Virginia

The Chesapeake Bay Local Assistance Program, Division of Environmental Engineering, Richmond, Virginia
C. Scott Crafton, Chief
W. Douglas Beisch, P.E., Senior Civil Engineer
Catherine M. Harold, Environmental Engineer

Gille Wilbanks, P.E., Consulting Engineer, Portland, Oregon

Charles Curtis, P.E. Site Technologies, Atlanta, Georgia

Tom Hunnicutt, P.E., Interlock Paving Systems, Hampton, Virginia

Thanks also goes to Harald von Langsdorff, Richard Bodie, Helga Piro, and Harry Cannon.

Years ago, two persons influenced my career by providing technical and philosophical foundations. They are Gary E. Day, AIA, Associate Professor of Architecture at the State University of New York in Buffalo, and John Randolph, Ph.D., Professor of Environmental Planning at Virginia Tech in Blacksburg. They teach that the opposing forces of urban development and nature's processes can be synthesized through practical operating principles and design tools. They also teach that, given the right tools, the gap between design that respects nature and cost-effective implementation is narrower still. A debt of thanks goes to Gary and John for providing me with those insights and tools, many of which are expressed in this manual.

Introduction

Compared to North America, Germany consumes about 12 times more per capita of interlocking concrete pavement annually. At least 15% of this is permeable interlocking concrete pavement. Permeable pavements are popular because the German approach to environmental protection is not simply based on attenuating impacts from development. They consider the benefits of the natural environment to society. Development must regenerate, maintain and enhance it. This notion is rooted in their word for environment, *umwelt*. Its meaning embraces the health and well-being of people and nature. North American English would translate the German notion of a healthy environment as environmental quality.

Infiltration trenches have been in use for decades as a means to reduce stormwater runoff and pollution, and to recharge groundwater. Recent experience has demonsrated that they work successfully when runoff is filtered prior to entering the pavement. From an engineering perspective, permeable interlocking concrete pavements are infiltration trenches with paving over them to support pedestrians and vehicles. Therefore, much of this manual is borrowed from literature and experience on infiltration trench design, construction and maintenance. It also borrows engineering from other kinds of permeable pavements.

This manual is written for civil engineers, architects, landscape architects and contractors. Those who use it should be familiar with stormwater management concepts and calculations such as the Rational Method and the National Resources Conservation Service (NRCS) Technical Release (TR) 55. They should be also familiar with the design of best management practices. The references cited with numbers in parentheses (e.g., (2)) throughout the text provide a wealth of information. The Glossary of Terms in Appendix A clarifies the meaning of many words and concepts used throughout the manual.

The manual does not portend to be complete, and it does not provide a "one stop" book for design. Rather, it provides criteria for selecting appropriate sites and the basics for sizing storage areas. Detailed inflow and outflow (stage-discharge) calculations are not covered because they vary considerably from site to site. Calculations must be done by a qualified engineer familiar with hydrology and hydraulics. Construction guidelines are provided as well as a maintenance checklist.

Permeable pavements should be incorporated into broader site designs and regenerative development that improves environmental quality, i.e., the health and well-being of people and nature. Permeable interlocking concrete pavements can do this more elegantly than other pavement, permeable or impervious. For example, they visually annunciate vehicular and pedestrian circulation, reduce micro-climatic temperatures, enhance tree growth and soften harsh visual transitions between building walls and the ground. A multitude of colors and patterns define areas and tie them to surrounding buildings and landscape. Sensitivity to these design concerns will improve the health, safety, and well-being of people and nature.

David R. Smith
Washington, D.C.
2005

Section 1. Selection

Impacts from Impervious Surfaces

Urbanization brings an increasing concentration of pavements, buildings, and other impervious surfaces. They generate additional runoff and pollutants during rainstorms, causing streambank erosion, as well degenerating lakes and polluting sources of drinking water. Increased runoff deprives ground water from being recharged, decreasing the amount of available drinking water in many communities. Figure 1 summarizes the impacts of impervious surfaces.

Increased Imperviousness leads to:	RESULTING IMPACTS				
	Flooding	Habitat Loss	Erosion	Streambed alteration	Channel widening
Increased volume	*	*	*	*	*
Increased peak flow	*	*	*	*	*
Increased peak flow duration	*	*	*	*	*
Increased stream temperature		*			
Decreased base flow		*			
Changes in sediment loadings	*	*	*	*	*

Figure 1. Impacts from increases in impervious surfaces (1).

Stormwater generates intermittent discharges of pollutants into water courses. Since the pollutants in stormwater runoff are not generated by a single, identifiable point source such as a factory, but from many different and spatially separated sources, they are called non-point sources of water pollution. During and after rainstorms, non-point sources of runoff pollution flow in huge quantities that render them untreatable by conventional wastewater treatment plants. In many cases, the receiving water cannot process the overwhelming amount of pollutants either. Therefore, the breadth of pollutants are difficult to control, as well as the extent to which they can be treated through nature's process in a lake, stream, or river.

Best Management Practices (BMPs)

U.S. federal law (2) has mandated that states control non-point source water pollution through the National Pollution Discharge Elimination System (NPDES) program. The law requires, among many things, that states identify and require best management practices, or BMPs, to control non-point source pollution from new development. BMPs are implemented typically through regional and local governments charged with water quality management, planning, and regulation.

BMPs include many technologies and land management practices for reducing the quantity of pollutants in stormwater. They are used in combination at the site, development and watershed scales to attain the maximum benefits to the stormwater drainage system. BMP's are divided into structural and non-structural practices. Structural BMPs capture runoff and rely on gravitational settling and/or the infiltration through a porous medium for pollutant reduction. They include detention dry ponds, wet (retention) ponds, infiltration trenches, sand filtration systems, and permeable and porous pavements. These are often used to offset increases in pollutants caused by new development (3).

Nonstructural BMPs involve a wider scope of practices. They can range from public awareness programs about preventing non-point water pollution to the use of natural techniques such as bio-retention and stormwater wetlands to enhance pollutant removal and promote infiltration of water into the ground.

Figure 2. Permeable interlocking concrete pavement combines stormwater infiltration, retention and parking into one place, thereby conserving land.

Many non-structural practices involve more efficient site planning. For example, these can include reducing the overall size of parking lots by reducing parking demand ratios, increasing shared parking, and use of mass transit credits. Many examples of nonstructural and structural practices can be found in *Better Site Design: A Handbook for Changing Development Rules in your Community* (4).

Permeable Interlocking Concrete Pavement— A Best Management Practice

Permeable interlocking concrete pavements are typically built on an open-graded, crushed stone base. The base offers infiltration and partial treatment of stormwater pollution and therefore, can be categorized as a structural BMP. Infiltration of rainfall helps maintain the balance of water in the soil, groundwater, and streams, thus supporting the water cycle. Besides reducing runoff, a certain degree of treatment occurs to the various pollutants in the water. Figure 2 illustrates a typical permeable interlocking concrete pavement.

If the infiltration capacity of the soil is exceeded, or there are particularly high levels of pollutants, the pavement base can be designed to filter, partially treat and slowly release water into a storm sewer or water course. When conditions allow, returning rainfall to the soil through infiltration is preferred over retaining the water and slowly releasing it into a sewer or water course.

Economics—Permeable interlocking concrete pavements may be cost-effective in new development where local regulations limit the total amount of impervious cover. However, they will be more expensive than using conventional (impervious) asphalt or concrete pavements and collecting the runoff (temporarily or permanently) in a pond. Nonetheless, the increased cost of using permeable interlocking concrete pavements may be recovered from the increase in rental income from more allowable space in the building. In other words, an increase in site coverage and rentable space may offset the additional cost of permeable pavement. The economic trade-offs of parking surface choices versus building space on the total amount of impervious cover should be reviewed on a project-by-project basis.

Permeable interlocking concrete pavements are especially cost-effective in existing urban development where there is a need to expand parking, but where there is not sufficient space for ponds. Therefore, the pavement can be used to conserve land because parking, stormwater infiltration and retention are combined into one facility.

The pavements are also cost-effective in areas where sewers flow at capacity during certain rainstorms. In these situations, replacing existing pipes with larger ones due to an increase in impervious cover from parking or buildings is not often economical. This solution merely transfers the additional runoff downstream and increases erosion and flooding potential.

Urbanized areas with an existing minimum of 50% impervious cover are typically where economics help decide the use of permeable pavement to conserve land or the

	Interlocking shapes with openings	Enlarged joints & spacers	Porous concrete units	Grid pavers with grass
Low-speed roads	Contact manufacturer	Contact manufacturer	Not recommended	Not recommended
Parking lots*/bays driveways	Excellent	Excellent	Not recommended	Acceptable for low use
Overflow parking, Access and emergency lanes	Excellent	Excellent	Not recommended	Good
Revetments, boat ramps	Good	Good	Not recommended	Good
Bike paths, Sidewalks* Pedestrian areas*	Good	Good (maintain narrow joints)	Excellent	Not recommended

Figure 3. Evaluation of applications for concrete permeable pavement.
**See design considerations for disabled persons on page 10.*

capacity of the drainage system. Economics suggests that design professionals should study the trade-offs between permeable interlocking concrete pavements and other best management practices for these areas.

Figure 4. Interlocking pavers can allow water through openings created by the paver shape.

Benefits and Limitations of Permeable Interlocking Concrete Pavements

This BMP essentially functions as an infiltration and retention area that can accommodate pedestrians, vehicular parking, and traffic. This combination of functions offers the following benefits:

- Conservation of space on the site and reduction of impervious cover
- Reduction of runoff by as much as 100% from frequent, low-intensity and short duration storms
- Reduction or elimination of unsightly retention basins in other parts of the drainage system
- Promotes tree survival by providing air and water to roots
- Preserves woods and open space that would have been destroyed for detention basins
- Reduces pollutants and improves water quality
- Reduction of runoff temperature
- Reduced peak discharges and stress on storm sewers
- Increased recharge of groundwater
- Reduction of downstream flows and stream bank erosion due to decreased peak flows and volumes
- Reduced overall project development costs due to a reduction in storm sewers and drainage appurtenances
- Eliminates puddling and flooding on parking lots
- Reduced snow plow costs due to rapid ice melt drainage
- Durable, high-strength, low-absorption concrete units resist freeze-thaw and heaving
- Reduces micro-climatic temperatures and contributes to urban heat island reduction
- Eligible for LEED® credits (see *ICPI Tech Spec 16—Achieving LEED® Credits with Segmental Concrete Pavements*)
- Immediately ready for traffic (no waiting days for curing)
- Can be placed over underground stormwater storage systems

Limitations are listed below and are addressed throughout the manual:

- Overall cost compared to other BMPs
- Greater site evaluation and design effort

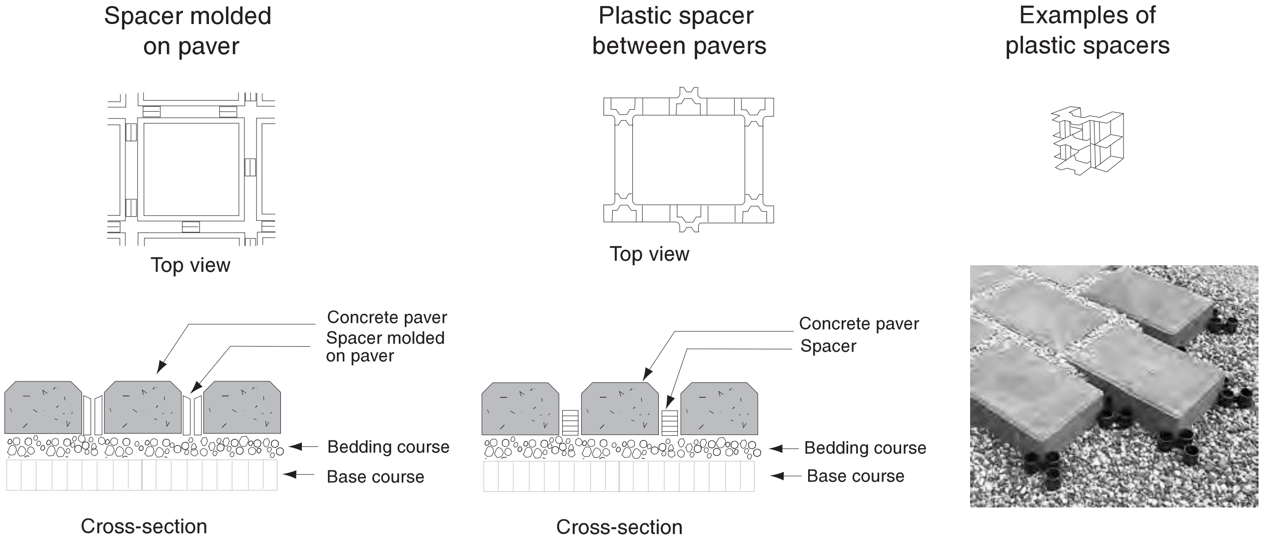


Figure 5. Methods of spacing units to accommodate aggregate in the joints (5).

- A higher level of construction skill, inspection, and attention to detail
- Surface maintenance to minimize clogging to ensure long-term performance.

Types of Permeable Paving Products Made With Concete

There are many different shapes and sizes of permeable interlocking concrete pavers. These can be grouped into three categories: interlocking shapes, enlarged permeable joints, and porous concrete units. Figure 3 lists the various types and rates their suitability in various applications (6). The table also lists concrete grid pavers for comparison purposes.

Interlocking shapes with openings—These have patterns that create openings or drainage holes for rainfall to enter, while maintaining high side-to-side contact among the units for stability under vehicular loads. Figure 4 shows one of many designs.

Figure 6. Joints can be filled with aggregate for infiltration or with topsoil and grass microclimatic cooling.

Enlarged permeable joint—These are pavers with wide joints for rainfall to enter. Joints can be as wide as $1^{3}/_{8}$ in. (35 mm). The joints are created with large spacers molded into the sides of each paver, or with plastic spacers inserted between each unit. These maintain consistent joints and stable units (Figure 5). Some units have spacers on them for laying either with a narrow joint for drainage filled with open-graded crushed stone, or with a wider joint for accommodating grass and topsoil (see Figure 6). Some joints may include indented sides or chambers in the sides of each unit that can store additional runoff (Figure 7).

Porous concrete units—The sponge-like appearance of the unit in Figure 8 allows rainfall to directly enter and pass through it because the concrete has no fines. Like other pavers, the units are tightly fitted together over bedding sand, compacted, joints filled with coarse, washed sand, and compacted again. Care must be taken to not allow joint sand to clog the openings in the surface of the units. Porous units often do not meet the requirements of ASTM C 936, and these types of units are appropriate in non-freeze-thaw areas only. Their use is best for pedestrian areas, bicycle paths, and residential applications.

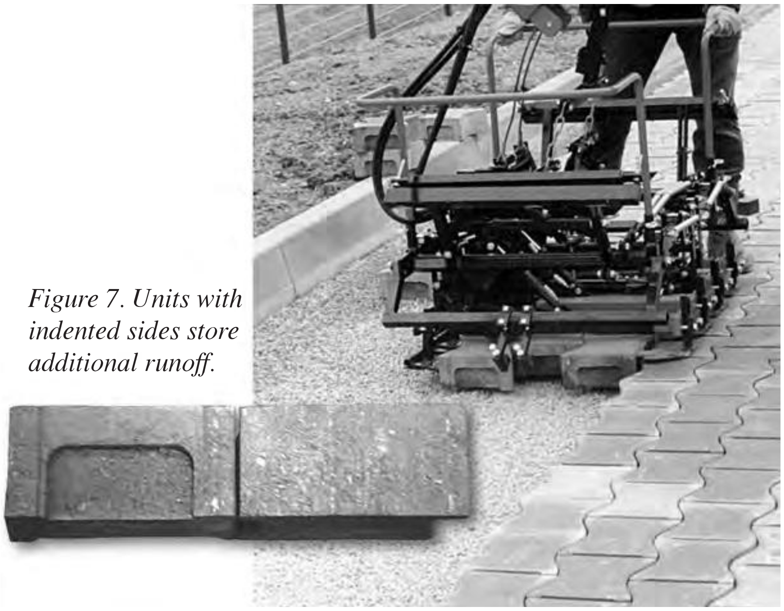


Figure 7. Units with indented sides store additional runoff.

Permeable pavers and concrete grid pavers—A related product, concrete grid pavers, is also a best management practice, and its design and construction are discussed in *ICPI Tech Spec 8—Concrete Grid Pavements* (5). Both concrete grid and solid permeable pavers can be placed on an open-graded base for enhanced runoff control, as well as on a dense-graded base. Grid pavers, however, have a different range of applications. They are intended for light-duty use such as over-flow parking areas, occasionally used areas in parking lots, and access and emergency lanes. In contrast, permeable pavers are intended for more heavily trafficked pavements such as regularly used parking lots and low-traffic volume streets. They have been used in industrial yards as well. Figure 9 illustrates solid, grid, and permeable pavers used in concert to satisfy pedestrian needs, bicycle parking, and vehicular support, as well as infiltration requirements.

Figure 8. Porous concrete units allow water directly into open-graded concrete.

Figure 9. Solid, grid, and permeable interlocking concrete pavers working in harmony to reduce water runoff and pollution, and to provide a more comfortable microclimate.

Infiltration Practices and Municipal Regulatory Approaches

The decision regarding whether to use infiltration practices including permeable pavements is guided by municipal policy and design criteria (plus experience). Site constraints (covered in detail later) are often the most influential factors. Design criteria and regulations vary across the continent due to different rainstorms, geographic locations and land-use development patterns. In most localities, BMPs are designed to a specific storm recurrance (or return period), duration, and intensity, e.g., a 2-year, 24-hour storm of 1.5 in./hr (33 mm/hr or 106 l/s/ha), or capture the volume from the first $^{1}/_{2}$ to 1 in. (13 to 25 mm).

A well-structured municipal stormwater management strategy will consider the influence of the region's range or spectrum of rainfall frequencies on the selection of BMPs. Each region has its own rainfall frequency distribution patterns. Different management practices can handle various volumes of runoff and pollution within portions of this spectrum. Figure 10 illustrates these overlapping ranges of rain storms, expressed in recurrence intervals. It also shows management objectives that can be achieved within those categories of recurrence and rainfall volume.

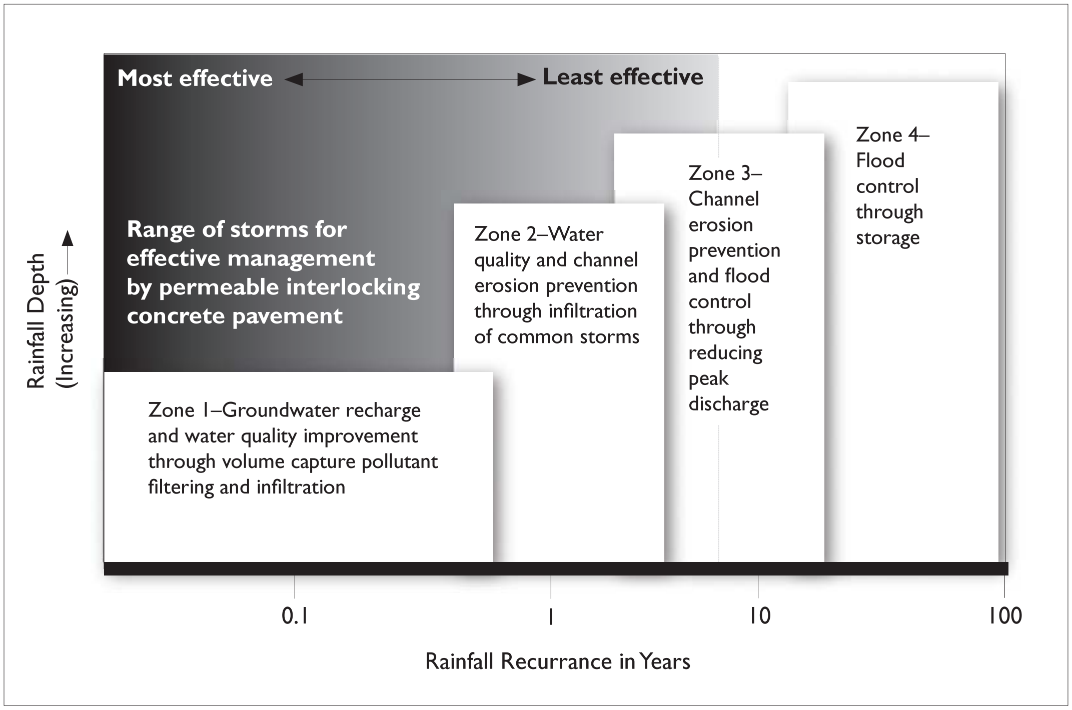


Figure 10. Rainfall Frequency Spectrum defines the distribution of all rainfall events for a region. It is a tool for applying and sizing permeable interlocking concrete pavements and other BMPs to treat pollutants and to control runoff quantities (after Schueler) (9).

Permeable interlocking concrete pavements absorb frequent, short duration storms. In most parts of North America, these comprise 75% to 85% of all rainstorms as suggested by Figure 10. If designed to handle bigger storms, runoff volumes can be decreased (with other BMPs) to help reduce peak discharges and erosion of drainage channels. While having some limited benefits, increased storage capacity of rainfall volume in the base can contribute some local flood control.

Various Municipal Regulatory Approaches—Some localities regulate both water quantity and quality. An example may be a city adjacent to a bay that needs to protect fishing and recreation industries. It may have criteria for reducing runoff and for various types of water pollutants such as nitrogen, phosphorous, metals and sediment. Water quality regulations are usually written to protect specific uses (e.g., drinking water, fishing, swimming, boating, etc.) of the body of water receiving the runoff. Other localities may only regulate runoff quantities, while recognizing that there will be a corresponding reduction of pollutants when using certain BMPs.

An increasing number of municipalities regulate the amount of impervious cover. This is often based on knowing the maximum capacity of public storm sewers and streams (for a given design storm), that can not be exceeded without flooding and property damage. More sophisticated analyses by some agencies have demonstrated a direct relationship between the amount of impervious cover and the pounds (or kg) of specific pollutants that will wash into receiving waters. In regulating the amount of impervious cover, as well as its configuration and hydrological connections, municipalities can control many pollutants washed by runoff into receiving waters.

Some municipalities have created stormwater utilities similar to water and sewer utilities. The legal rationale for a stormwater utility is rain falls on private property belongs to the property owner. Therefore, removal of runoff from private property through a municipal drainage system should be paid by the property owner to the local municipal utility.

The fee charged by the municipality for this service depends on how much water is discharged from each property. The fee is based on the amount of impervious area, impervious and gross area, or an additional intensity-of-use factor. Since the fees go specifically to managing stormwater, the charge is not considered a tax that pays for a wider range of city services. Typically, fees are used by the municipality for managing stormwater through maintaining and expanding the municipal drainage system. In some instances, fees are also used to restore damaged streams and riparian habitats.

A residential property owner pays a lower fee for stormwater removal while a shopping center owner pays a higher fee due to generating more runoff from a high area of roofs and parking lots. An owner's fee may be reduced if there is reduction of impermeable surfaces such as pavement, or if the water is stored on the owner's site in retention or detention ponds. Permeable interlocking concrete pavement systems are pervious and offer storage. Therefore, a strong rationale exists for *reduction* of storm water utility fees for owners who use this pavement.

Section 2. Design

Municipal Stormwater Management Objectives

The intent of many regional authorities, drainage districts, counties, cities and towns aim at preservation of natural drainage and treatment systems, or limit flows to drainage systems especially if they are working at or near capacity. Some agencies achieve this through a comprehensive stormwater management plan including operation and maintenance administered through stormwater utilities. Some governments use stormwater modeling and field calibration of watersheds and watercourses in their jurisdiction. Modeling can range from simple formulas like the Rational Method, NRCS TR-55 or more sophisticated models such as HEC or EPA SWMM. These results inform drainage design guidelines for specific site development proposals brought to a government for approval. Sophisticated modeling can also demonstrate specific downstream impacts from a specific development proposal.

In approaching site design, municipalities incorporate some or all of the following design goals for managing stormwater.

1. Reduce the generation of additional stormwater and pollutants by restricting the growth of impervious surfaces.
2. Treat runoff to remove a given percentage of a pollutant or pollutants from the average annual post-development load. Target pollutant reductions can include total suspended solids (TSS) (typically 80% reduction) and total phosphorous (TS) (typically 40% reduction) as these are primary indicators of water quality. Reductions are measured on a mass basis.
3. Capture and treat a specific water quality volume defined as the initial depth of rainfall on a site (typically ranging from 0.75 in to 1.5 in. or 18 to 40 mm). This volume generally contains the highest amount of pollutants.
4. Enhance stream channel protection through extended detention (and infiltration) of runoff volume from a given storm event, e.g., a 1 or 2 year 24-hour storm. The difference in volumes between pre- and post development is often detained, infiltrated and/or slowly released.
5. Provide streambank erosion prevention measures such as energy dissipation and velocity control plus preservation of vegetative buffers along a stream.
6. Reduce overbank flooding through reducing the post-development peak discharge rate to the pre-development rate for a given storm, e.g., a 25-year, 24-hour event.
7. Reduce the risk of extreme flooding by controlling and/or safely conveying the 100-year, 24-hour return frequency storm event. This goal is also supported by preserving existing and future floodplain areas from development or restricting it in them as much as possible.
8. Maintain groundwater recharge rates to maintain stream flows and ecosystems as well as recharging aquifers.
9. Prevent erosion and sedimentation from construction through control practices provided on site development plans inspected during construction.

Permeable interlocking concrete pavements can play an important role in reaching all of these goals. These pavements help meet these goals with full, partial or no exfiltration of the open-graded stone base into the soil subgrade.

Figure 11. Portland, Oregon renovated streets with about 20,000 sf (2,000 m^2) of permeable interlocking concrete pavement after water and sewer line repairs in an older neighborhood. The city incorporated modeling to evaluate this pavement. The pavement decreased combined sewer overflows to the waste treatment plant and discharges into the Willamette River.

Full or Partial Exfiltration

A design for full exfiltration means the water infiltrates directly into the base and exfiltrates to the soil. This is the most common application. Overflows are managed via perimeter drainage to swales, bio-retention areas or storm sewer inlets.

Partial exfiltration does not rely completely on exfiltration of the base into the soil to dispose of all the captured runoff. Some of the water may exfiltrate into the soil while the remainder is drained by perforated pipes. Excess water is drained from the base by pipes to sewers or a stream. Figures 12 and 13 show schematic cross-sections of full and partial exfiltration designs.

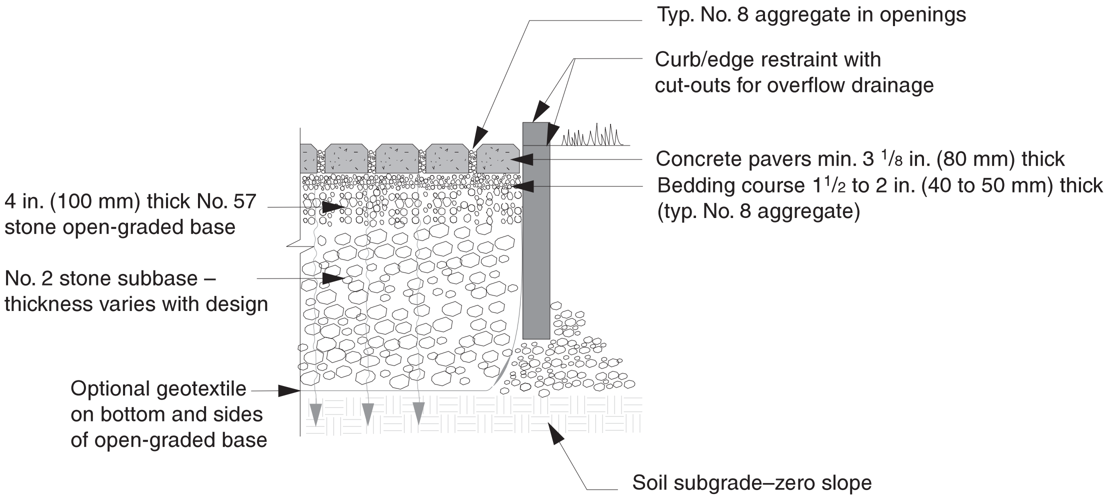


Figure 12. ***Full exfiltration*** *through the soil surface. Overflows are managed via perimeter drainage to swales, bio-retention areas or storm sewer inlets.*

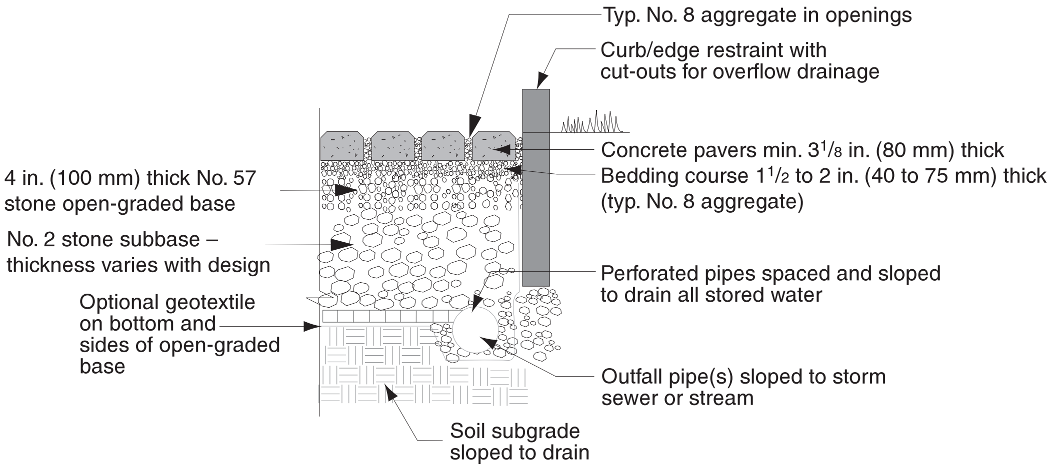


Figure 13. ***Partial exfiltration*** *through the soil. Perforated pipes drain excess runoff that cannot be absorbed by slow-draining soil.*

No Exfiltration

No exfiltration is required when the soil has low permeability and low strength, or there are other site limitations. An impermeable liner may be used if the pollutant loads are expected to exceed the capacity of the soil and base to treat them. The liner can be high density polyethylene (HDPE), ethylene propylene diene monomer (EPDM), rubber asphalt, or asphalt-based materials. Manufacturers of these materials should be consulted for application guidance. A liner may also be used if the depth to bedrock or to the water table is only a few feet (0.6 to 0.8 m). By storing water in the base for a time and then slowly releasing it through pipes, the design behaves like an underground detention pond. Figure 14 illustrates a cross-section design for no base exfiltration into the soil. In some cases, the soil may be stabilized to render improved support for vehicular loads. This practice almost reduces infiltration into the soil to practically zero.

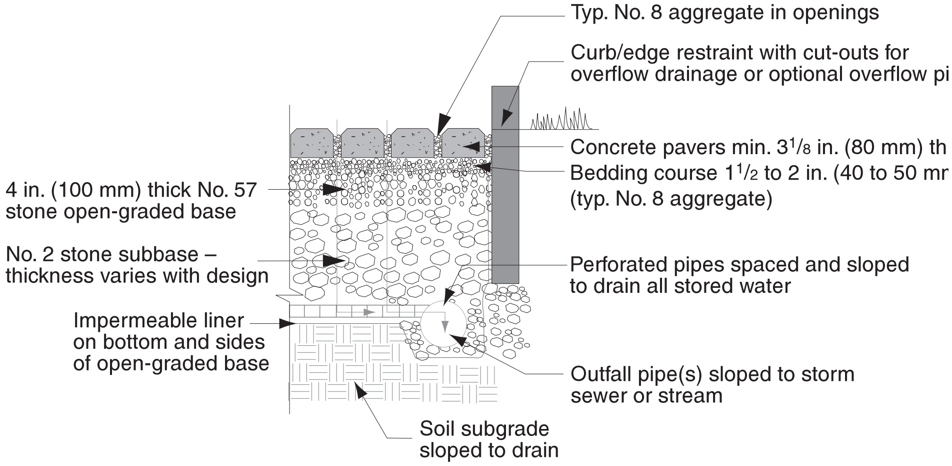


Figure 14. No exfiltration of water from the base is allowed into the soil due to the use of an impermeable liner at the bottom and sides of the base. Perforated drain pipes are sized to slowly release the water into a sewer or stream.

There are four situations where permeable interlocking concrete pavements should not exfiltrate. Instead, an impermeable liner is used to capture, store and release runoff from the base.

- When the depth from the bottom of the base to the high level of the water table is less than 2 feet (0.6 m), or when there is not sufficient depth of soil to offer adequate filtering and treatment of water pollutants.
- Directly over solid rock, or over solid rock with no loose rock layer above it.
- Over aquifers with insufficient soil depth to filter the pollutants before entering the ground water. These can include karst, fissured or cleft aquifers.
- Over fill soils, natural or fill, whose behavior when exposed to infiltrating water may cause unacceptable behavior. This might include expansive soils such as loess, poorly compacted soils, gypsiferous soils, etc.

While these limitations may not be present, the soil may still have low permeability. In these cases, the soil may hold the water in the base for slow drainage while providing a modest amount of infiltration. In a few cases, soil profiles may offer a more permeable layer further below the pavement. It may be cost-effective to drain the water via a french drain or pipes through the impermeable layer of soil under the base and into the lower soil layer with greater permeability.

Site Selection Criteria

Permeable interlocking concrete pavements are recommended in areas with the following site characteristics (11):

- Residential walks and driveways.
- Walks, parking lots, main and service drives around commercial, institutional, recreational and cultural buildings.
- Boat ramps and non-commercial boat landings (often owned by local, state or provincial recreation agencies).

- Industrial sites that do not receive hazardous materials, i.e., where there is no risk to groundwater or soils from spills.
- Storage areas for shipping containers with non-hazardous contents.
- The impervious area does not exceed five times the area of the permeable pavement receiving the runoff.
- The estimated depth from the bottom of the pavement base to the high level of the water table is greater than 2 feet (0.6 m). Greater depths may be required to obtain additional filtering of pollutants through the soil.
- The pavement is downslope from building foundations, and the foundations have piped drainage at the footers.
- The slope of the permeable pavement surface is at least 1% and no greater than 5%.
- Land surrounding and draining into the pavement does not exceed 20% slope.
- At least 100 ft (30 m) should be maintained between permeable pavements and water supply wells, streams, and wetlands. (Local jurisdictions may provide additional guidance or regulations.)
- Sites where the owner can meet maintenance requirements (see maintenance section).
- Sites where there will not be an increase in impervious cover draining into the pavement (unless the pavement is designed to infiltrate and store runoff from future increases in impervious cover).
- Sites where space constraints, high land prices, and/or runoff from additional development make permeable interlocking concrete pavements a cost-effective solution.

Permeable interlocking concrete pavements are not recommended on any site classified as a stormwater hotspot, i.e., if there is any risk that stormwater can infiltrate and contaminate groundwater. These land uses and activities may include the following:

- Vehicle salvage yards, recycling facilities, fueling stations, service and maintenance facilities, equipment and cleaning facilities
- Fleet storage areas (bus, truck, etc.)
- Commercial marina service and maintenance areas
- Outdoor liquid container storage areas
- Outdoor loading/unloading facilities
- Public works materials/equipment storage areas
- Industrial facilities that generate or store hazardous materials
- Storage areas for commercial shipping containers with contents that could damage groundwater and soil
- Land uses that drain pesticides and/or fertilizers into permeable pavements (e.g., agricultural land, golf courses, etc.)
- Other land uses and activities as designated by an appropriate review authority

Design Considerations for Pedestrians and Disabled Persons

Before a parking lot or plaza is constructed, existing pedestrian paths across the lot should be studied and defined. Vehicle lanes, parking spaces, pedestrian paths, and spaces for disabled persons can be delineated with solid concrete pavers. Paths with solid units will make walking more comfortable, especially for pedestrians with high-heeled shoes and for the elderly. Likewise, parking spaces accessible to disabled persons and for bicycles should be marked with solid pavers. Permeable interlocking concrete pavers with openings or wide joints should not be used in disabled-accessible parking spaces or on pedestrian ramps at intersections.

Infiltration Rates of Permeable Interlocking Concrete Pavement Systems

A common error in designing permeable interlocking concrete pavements is assuming that the amount or percent of open surface area is equal to the percent of perviousness. For example, an 18% open surface area is incorrectly assumed to be 18% pervious, or 82% impervious. The perviousness and amount of infiltration are dependent on the infiltration rates of joint filling material, bedding layer, and base materials, not the percentage of surface open area.

Compared to soils, permeable interlocking concrete pavements have a very high degree of infiltration. For example, a clay soil classified as CL using the Unified Soil Classification System might have an infiltration rate in the order of 1.4 x 10^{-5} in./hr (10^{-9} m/sec). A silty sand (SM) could have 1.4 x 10^{-3} in./hr (10^{-7} m/sec) infiltration rate. Open-graded, crushed aggregate placed in the openings of permeable interlocking concrete pavements will have an initial infiltration over 500 in./hr (over 10^{-3} m/sec), i.e, 10,000 times greater than the sandy soil and 100,000 times greater than the clay soil. The open-graded base material has even higher infiltration, typically 500 to 2,000 in./hr (10^{-3} to 10^{-2} m/sec). Therefore, the small percentage of open surface area is capable of providing a large amount of infiltration into the pavement.

Regardless of the high infiltration rate of the aggregates used in the openings and base, a key consideration is the lifetime *design* infiltration of the *entire* pavement cross-section, including the soil subgrade. Its infiltration rate is difficult to predict over time. There can be short-term variations from different amounts of antecedent water in it, and long-term reductions of infiltration from partially clogged surface or base, geotextiles or soil subgrade. So a conservative approach should always be taken when establishing the design infiltration rate of the pavement system.

Studies on permeable interlocking concrete pavers have attempted to estimate their long-term infiltration performance. Permeable concrete units (made with no fine aggregates) demonstrate lowest average permeability. Interlocking shapes with openings or those with enlarged permeable joints offer substantially higher infiltration performance over the long term.

Research on permeable pavements made with solid, nonporous units provides some guidance on long-term infiltration rates. German studies (6)(7)(8)(12), ICPI (43), and a review of the literature by Ferguson (44) reviewed parking lots with open-graded materials in the paver openings over an open-graded base. They showed a high initial infiltration when new and a decrease and leveling off as they aged. The decrease in infilitration is natural and is due to the deposit of fine materials in the aggregate fill and clogging of the base and geotextiles.

When tested, new pavements demonstrated very high surface infiltration rates of almost 9 in./hr (6 x 10^{-5} m/sec) and two four-year old parking lots indicated rates of about 3 in./hr (2 x 10^{-5} m/sec). Lower rates were exhibited on pavements where openings were filled with sand or aggregate and itinerant vegetation. In another study of two and five-year old parking lots, the infiltration rates were about 6 and 5 in./hr (4 and 3.5 x 10^{-5} m/sec) respectively. Infiltration was measured over approximately one hour for these two studies. In an ICPI study (44) ten sites indicated 1$^1/_2$ in./hr to over 780 in./hr. The lowest infiltration rates were sites clogged with fines.

The results of these studies confirm that the long-term infiltration rate depends on the intensity of use and the degree to which the surface and base receive sediment. This is also confirmed in the literature on the performance of infiltration trenches. Since there are infiltration differences between initial and long-term performance, construction, plus inevitable clogging, **a conservative design rate of 3 in./hr (2.1 x 10^{-5} m/sec or 210 L/sec/hectare) can be used as the basis for the design surface infiltration rate for a 20-year life**. This design infiltration rate will take in most storms.

Site Design Data

Desktop Assessment

A preliminary assessment should be conducted prior to detailed site and hydrological design. This initial assessment includes a review of the following:

- Underlying geology and soils maps
- Identifying the NRCS hydrologic soil groups (A, B, C, D)
- Verifying history of fill soil or previous disturbances or compaction
- Review of topographical maps and identifying drainage patterns
- Identifying streams, wetlands, wells and structures
- Confirming absence of stormwater hotspots
- Identifying current and future land uses draining onto the site

Rainfall and Traffic Data

The following data will be necessary to design the pavement:

1. The total area and percent of impervious surface draining on the permeable pavement.
2. The design storm with the return period and intensity in inches or millimeters per hour (usually supplied by municipality or other regulatory agency). Rainfall intensity-duration-frequency maps can be referenced to establish the design storm (13) (14).
3. The volume of runoff or peak flow to be captured, exfiltrated, or released using the design storm.
4. An estimate of the vehicular traffic loads expressed as 18,000 kip (80 kN) equivalent single axle loads (ESALs) over the design life of the pavement, typically 20 years.

Soil Subgrade Sampling and Analysis

The soil sampling and testing program should be designed and supervised by a licensed professional engineer knowledgeable of the local soils. This engineer should provide assessment of design strength, permeability, compaction requirements and other appropriate site assessment information. Some suggested guidelines follow on sampling and testing procedures.

Test pits dug with a backhoe are recommended for every 7,000 sf (700 m^2) if paving with a minimum of two holes per site. All pits should be dug at least 5 ft (1.5 m) deep with soil logs recorded to at least 3 ft (1 m) below the bottom of the base. More holes at various depths (horizens) may be required by the engineer in areas where soil types may change, near rock outcroppings, in low lying areas or where the water table is likely to be within 8 ft (2.5 m) of the surface. Evidence of a high water table, impermeable soil layers, rock or dissimilar layers may require a base design with no exfiltration.

The following tests are recommended on soils from the test pit, especially if the soil has clay content. These assist in evaluating the soil's suitability for supporting traffic in a saturated condition while exfiltrating. Other tests may be required by the design engineer. AASHTO tests equivalent to ASTM methods may be used.

1. Unified (USCS) soil classification using the test method in ASTM D 2487 (15).
2. Sampled moisture content in percent.
3. Onsite tests of the infiltration rate of the soil using local, state or provincial recommendations for test methods and frequency. All tests for infiltration should be done at the elevation corresponding to the bottom of the base. If there are no requirements for infiltration test methods, ASTM D 3385 (18), Test Method for Infiltration Rate of Soils in Field Using a Double-Ring Infiltrometer is recommended. ASTM D 5093 (19), Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer with a sealed Inner Ring is for soils with an expected infiltration rate of 1.4 x 10^{-2} in./hr (10^{-7} m/sec) to 1.4 x 10^{-5} in./hr (10^{-10} m/sec). Percolation test results for the design of septic drain fields are not suitable for the design of stormwater infiltration systems (20).

Caution: Results from field tests are approximations because the structure and porosity of soils are easily changed. On-site tests do not account for loss of the soil's conductivity from construction, compaction and clogging from sediment. Nor do they account for lateral drainage of water from the soil into the sides of the base. Individual test results should not be considered absolute values directly representative of expected drawdown of water from the open-graded base. Instead, the test results should be interpreted with permeability estimates based on soil texture, structure, pore geometry and consistence (20).

For design purposes, a factor of safety of 2 should be applied to the average or typical measured site soil infiltration rate. For example a site infiltration rate of 1.0 in./hr is halved to 0.5 in./hr. for design calculations. This helps compensate for decreases in infiltration during construction and over the life of the permeable pavement. A higher factor of safety may be appropriate for sites with highly variable infiltration rates due to different soils or soil horizons.

USCS Soil Classification	Typical ranges for Coefficient of Permeability, k, in./hour (approximate m/s)	Relative Permeability when compacted and saturated	Shearing strength when compacted	Compressibility	Typical CBR Range
GW-well graded gravels	1.3 to 137 (10^{-5} to 10^{-3})	Pervious	Excellent	Negligible	30-80
GP-poorly graded gravels	6.8 to 137 (5×10^{-5} to 10^{-3})	Very pervious	Good	Negligible	20-60
GM-silty gravels	1.3×10^{-4} to 13.5 (10^{-8} to 10^{-4})	Semi-pervious to impervious	Good	Negligible	20-60
GC-clayey gravel	1.3×10^{-4} to 1.3×10^{-2} (10^{-8} to 10^{-6})	Impervious	Good to fair	Very low	20-40
SW-well graded sands	0.7 to 68 (5×10^{-6} to 5×10^{-4})	Pervious	Excellent	Negligible	10-40
SP-poorly graded sands	0.07 to 0.7 (5×10^{-7} to 5×10^{-6})	Pervious to semi-pervious	Good	Very low	10-40
SM-silty sands	1.3×10^{-4} to 0.7 (10^{-9} to 5×10^{-6})	Semi-pervious to impervious	Good	Low	10-40
SC-clayey sands	1.3×10^{-5} to 0.7 (10^{-9} to 5×10^{-6})	Impervious	Good to fair	Low	5-20
ML-inorganic silts of low plasticity	1.3×10^{-5} to 0.07 (10^{-9} to 5×10^{-7})	Impervious	Fair	Medium	2-15
CL-inorganic clays of low plasticity	1.3×10^{-5} to 1.3×10^{-3} (10^{-9} to 10^{-8})	Impervious	Fair	Medium	2-5
OL-organic silts of low plasticity	1.3×10^{-5} to 1.3×10^{-2} (10^{-9} to 10^{-6})	Impervious	Poor	Medium	2-5
MH-inorganic silts of high plasticity	1.3×10^{-6} to 1.3×10^{-5} (10^{-10} to 10^{-9})	Very impervious	Fair to poor	High	2-10
CH-inorganic clays of high plasticity	1.3×10^{-7} to 1.3×10^{-5} (10^{-11} to 10^{-9})	Very impervious	Poor	High	2-5
OH-organic clays of high plasticity	Not appropriate under permeable interlocking concrete pavements				
PT-Peat, mulch, soils with high organic content	Not appropriate under permeable interlocking concrete pavements				

Figure 15. Suitability of soils (per the Unified Soils Classification System) for infiltration of stormwater and bearing capacity (21)(22)(23). This table provides general guidance. Testing and evaluation of soils are recommended.

When designing for full exfiltration in vehicular applications a minimum tested soil infiltration rate of 0.52 in./hr (3.7×10^{-6} m/sec) is required. Some sites may require higher rates and there may be cases where lower rates are used. Local requirements for the design of infiltration trenches may also specify minimum rates.

Soils with a tested permeability equal to or greater than 0.52 in./hr (3.7×10^{-6} m/sec) usually will be gravel, sand, loamy sand, sandy loam, loam, and silt loam. These are usually soils with no more than 10-12% passing the No. 200 (0.075 mm) sieve. These are characterized as A and B hydrologic group soils using the NRCS classification system. Silt and clay soils will likely have lower permeability and not be suitable for full exfiltration from an open-graded base. For cold climates in the northern U.S. and Canada, the lowest recommended design infiltration rate for the soil subgrade is 0.25 in./hr (2×10^{-6} m/sec).

To help maximize infiltration, the subgrade should have less than 5% passing the No. 200 (0.075 mm) sieve, although soils with up to 25% passing may drain adequately depending on site conditions and specific characteristics. Soils with a permeability lower than 0.52 in./hr (3.7×10^{-6} m/sec) can be used to infiltrate water as long as the soil remains stable while saturated, especially when loaded by vehicles. However, drain pipes will be required. Soil stability under traffic should be carefully reviewed for each application by a qualified geotechnical or civil engineer. Pedestrian applications not subject to vehicular traffic can be built over soils with a lower permeability.

Figure 15 characterizes the permeability of soils using the Unified Soil Classification System (USCS). It also shows typical ranges of the California Bearing Ratio (CBR) values for these classifications. These are general guidelines and do not substitute for laboratory and field testing.

This design procedure assumes a soil CBR (minimum 96-hour soaked per ASTM D 1883 or AASHTO T 193 (7)) strength of at least 5% or an R-value of 24 to qualify for use under vehicular traffic. The compaction required to achieve this will greatly reduce the infiltration rate of the soil. Therefore, the permeability or infiltration rate of soil should be assessed at the density required to achieve 5% CBR. If soils have a lower soaked CBR or are highly expansive, they should be treated to raise the CBR above 5%. Treatment can be with cement, lime or lime/flyash (to control expansive soils) while raising the CBR. Guidelines on the amount and depth of cement required for soil stabilization can be found in reference 24 by the Portland Cement Association.

An alternative approach to raising the CBR of non-expansive soils to over 5% is by placing a capping layer of compacted crushed stone on the subgrade. The layer should have a minimum soaked CBR of 20% and be a minimum of 8 in. (200 mm) thick. Geotextile is recommended between these layers and the soil subgrade.

Soil Compaction

Soil compaction will decrease the infiltration rate of the soil. Compaction and decreased soil infiltration can shorten design life unless the anticipated decrease in soil infiltration from deliberate compaction is factored into the design infiltration rate of the soil. As noted later, use and diligent site control of tracked construction equipment traversing excavated soil subgrade will minimize its inadvertent compaction. Wheeled construction equipment should be kept from the excavated soil as these tend to concentrate loads, stress and compaction.

Pedestrian applications shouldn't require soil subgrade compaction and it should be avoided if possible for vehicular applications. As a general rule, most installations will be over undisturbed native soils. Soil excavations will typically be 2 to 3 ft (0.6 to 0.9 m) deep and cut into consolidated soil horizons that exhibit some stability when wet. For vehicular applications, this subgrade layer should be evaluated by a qualified civil or geotechnical engineer for the need for compaction while infiltration test pits are dug. In many cases, this layer should not require compaction except for static rolling after grading to provide a smooth subgrade surface to check final grades, accept geotextiles and pipe as appropriate, and the No. 2 stone subbase.

Some heavier clay soils will require compaction to gain stability when wet. These will likely be soils with low CBRs (<4%) and have low infiltration rates prior to compaction. Compaction may make little difference to already low infiltration rates. In such cases, these designs will include partial exfiltration using perforated pipes to drain remaining water at the bottom of the base/subbase reservoir.

There are other factors on sites not specifically covered in this manual that influence design decisions. The guidance of an experienced civil or geotechnical engineer familiar with local site conditions and stormwater management should be sought to confirm the suitability of the soil characteristics and possible treatments for use under all permeable interlocking concrete pavements.

Geotextiles and Filter Layers

Fines particles suspended in slowly moving water will be deposited in the pores of the adjacent material. In the case of permeable interlocking pavements, particles will be deposited in another soil, the aggregate base, bedding course, the aggregate in the pavement openings or geotextile.

The build-up of fines eventually clogs and reduces permeability of these materials. To reduce this action, filter criteria must be met whenever there is a change in materials. Criteria must be met for joint and bedding materials (if different materials are used), the bedding course, the bedding course and the base, base and sub-base, and the soil subgrade. While aggregate materials can be used for filters, the use of geotextiles is more common. Figure 16 provides geotextile filter criteria from the U.S. Federal Highway Administration (FHWA) (25) and the American Association of State Highway and Transportation Officials (AASHTO) (26).

An aggregate subbase consisting of ASTM No. 2 crushed stone can be used in lieu of geotextile. This material ranges in size from 2 ½ in. to ¾ in. (63 to 19 mm) and provides a stable working platform for construction equipment to spread and compact the No. 57 stone base. After compacting the No. 2 stone, No. 57 stone is spread and compacted or choked into the openings of the No. 2 stone which rests directly on the soil subgrade.

Materials for the Base, Bedding and Openings

The following data is required on materials for the base and subbase, bedding course, and aggregate in the pavement openings:

1. Sieve analysis, including washed gradations per ASTM C 136.
2. Void space in percent for the open-graded base per ASTM C 29.

Crushed stone, open-graded subbase and base—This material should be a hard, durable rock with 90% fractured faces and a Los Angeles (LA) Abrasion of < 40. A minimum effective porosity of 0.32 and a design CBR of at least 80% are recommended. A water storage capacity of open-graded

U.S. Federal Highway Administration (FHWA)

For fined grained soils with more than 50% passing the No. 200 (0.075 mm) sieve:

Woven geotextiles: Apparent Opening Size (AOS) $\le D_{85}$
Nonwoven geotextiles: $AOS_{geotextile} \le 1.8D_{85\ soil}$
AOS $\le$ 0.3 mm or $\ge$ No. 50 sieve

For granular soils with 50% or less passing the No. 200 (0.075 mm) sieve:

All geotextiles $AOS_{\ geotextile} \le B \times D_{85soil}$
Where:
$B = 1$ for $2 \ge C_U \ge 8$
$B = 0.5$ for $2 < C_U < 4$
$B = 8/C_U$ for $4 < C_U < 8$
$C_U = D_{60}/D_{10}$

Permeability criteria: k (fabric) $\ge$ k (soil)

Clogging criteria
Woven: Percent of open area $\ge$ 4%
Nonwoven: Porosity $\ge$ 30%

American Association of State Highway and Transportation Officials (AASHTO)

For soils $\le$ 50% passing the No. 200 (0.075 mm) sieve:
$O_{95} < 0.59$ mm ($AOS_{fabric} \ge$ No. 30 sieve)

For soils > 50% passing the No. 200 sieve:
$O_{95} < 0.30$ mm ($AOS_{fabric} \ge$ No. 50 sieve)

Notes:

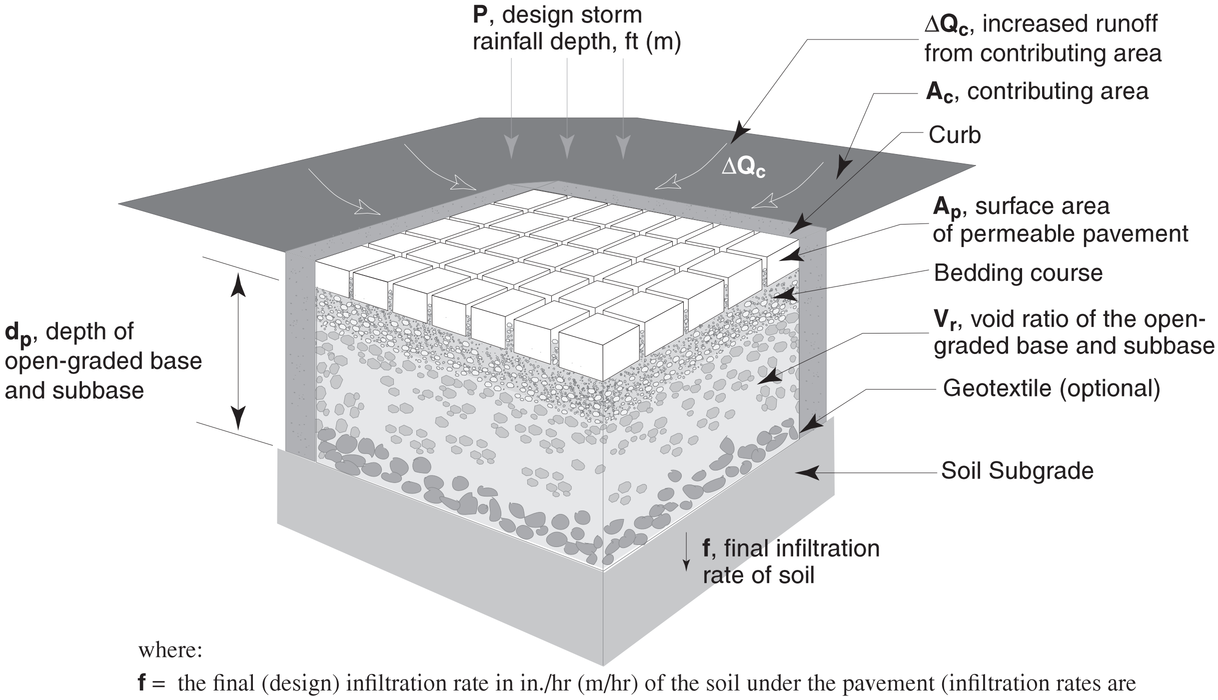
1. D_x is particle size at which x percent of the particles are finer. Determined from gradation curve. Example: D_{10} is the size particle of a soil or aggregate gradation for which 10% of the particles are smaller and 90% are coarser.
2. O_x is geotextile size corresponding to x particle size base on dry glass bead sieving. Hence O_{95} is the geotextile size opening for which 95% of the holes are smaller.
3. AOS is apparent opening size is essentially the same but normally defined as a sieve number rather than as a size (ASTM D 4751). POA is percent open area for (woven fabrics only). Permeability, k of the soil and geotextile (nonwoven only) are designated k_S and k_G respectively.

Figure 16. Geotextile filter criteria

subbase and base will vary with their depth and the percent of void spaces in them. The void space of open-graded aggregate can be supplied by the quarry or from independently conducted tests.

The in-situ aggregate subbase and base should have a porosity of at least 0.32 to allow void space for water storage. The structural strength of these materials should be adequate for the loads to which it will be subjected. ASTM No. 57 crushed aggregate is commonly used for open-graded bases and ASTM No. 2 for subbase. They are recommended for most permeable pavement applications. They often have a porosity (volume of voids ÷ total volume of the base) over 0.32 and storage capacity in its void spaces (volume of voids ÷ volume of aggregate), typically 20% to 40%. A 40% void space means that the volume of the base will need to be 2.5 times the volume of the water to be stored.

The large size of the aggregates in No. 57 crushed stone creates an uneven surface when compacted. To smooth the surface, a bedding course of ASTM No. 8 crushed aggregate is placed and compacted into the top of the No. 57 open-graded base. The No. 8 bedding material is often called choke stone since it stabilizes and partially chokes or closes the surface of the open-graded base. The thickness of the No. 8 bedding layer should not exceed 2 in. (50 mm) prior to compaction. Like No. 57, it should be hard material, having 90% fractured faces and an LA Abrasion < 40. The infiltration rate should be at least 1,000 in./hr (7 x 10^{-3} m/sec). The No. 8 material stabilizes the



where:

f = the final (design) infiltration rate in in./hr (m/hr) of the soil under the pavement (infiltration rates are determined from permeability tests and engineering judgement);

$\mathbf{T_s}$ = the maximum allowable storage time of 72 hours; and

$\mathbf{V_r}$ = the void ratio (space) of the crushed stone base and subbase (min. 0.32, typically 0.4).

The maximum allowable depths are given in Figure 19 for selected values of **f**, $\mathbf{T_s}$, and $\mathbf{V_r}$.

$\mathbf{A_c}$ = contributing area, sf (m^2)

$\Delta \mathbf{Q_c}$ = increased runoff from contributing area, ft (m) per a given design storm

$\mathbf{A_p}$ = surface area of permeable interlocking concrete pavement, sf (m^2)

P = design storm rainfall depth, ft (m)

$\mathbf{d_p}$ = depth of crushed stone base, ft (m)

T = effective filling time of the base, hours (2 hours is typical)

Figure 17. Design parameters for calculating the base depth for permeable interlocking concrete pavements.

surface of the No. 57 and provides some filtering of water. Therefore the No. 8 choke stone should meet the following criteria:

$$D_{15 \text{ open-graded base}} / D_{50 \text{ choke stone}} < 5 \text{ and } D_{50 \text{ open-graded}} / D_{50 \text{ choke stone}} > 2$$

D_x is the particle size at which x percent of the particles are finer. For example, D_{15} is the particle size of a soil or aggregate gradation for which 15% of the particles are smaller and 85% are coarser.

If the bedding material can't meet this filter criteria (i.e., the bedding stone is smaller or the base material is larger), a layer of geotextile may be used between the bedding and base course. This adds stability to the structure. Geotextile has been shown to accelerate digestion of oils through moisture and microbial action (45).

Besides use as a bedding material, No. 8 crushed stone aggregate is also recommended for fill material in the paver openings. Smaller sized aggregate such as No. 89 may be needed to enter narrow joints between interlocking shapes. Ferguson (43) provides additional filter criteria for aggregate layers. The void space in the bedding and joints is not considered in water storage calculations. Nonetheless, they provide an additional factor of safety since they have capacity for storing water.

Concrete units for permeable pavement—The following data is needed on the pavers:

1. Minimum thickness = 3$^1/_8$ in. (80 mm) for vehicular applications and 2$^3/_8$ in. (60 mm) for pedestrian applications. For pedestrian applications joint widths should be no greater than $^3/_4$ in. (15mm). Smaller stone such as No. 9 or No. 10 should be considered for filling the joints as this will lend greater interlock.
2. Percent of open area of the surface.
3. Test results indicating conformance to ASTM C 936, *Standard Specification for Solid Interlocking Concrete Paving Units* (27), or CSA A231.2, *Precast Concrete Pavers* (28) as appropriate. If the dimensions of the units are larger than those stated in these standards, then CSA A231.1, *Precast Concrete Paving Slabs* (29) is recommended as a product standard.

Sizing an Open-Graded Base for Stormwater Infiltration and Storage

The following design method is adapted from *Standard Specifications for Infiltration Practices* (30) and the *Maryland Stormwater Manual* published by the State of Maryland, Department of the Environment (31). The procedure is from "Method for Designing Infiltration Structures." This method assumes familiarity with NRCS TR 55 method (32) for calculating stormwater runoff. References 11, 33, 34, and 35 provide other methods. Provinces, states, and cities may mandate the use of other methods. The Maryland method is provided because it has been refined over many years and it illustrates important aspects of infiltration design.

Like porous asphalt pavement, permeable interlocking concrete pavement relies on an open-graded aggregate base into which water rapidly infiltrates for storage. The pavement base functions as an underground detention structure. Therefore, pavement base storage can be designed with the same methods as those used for stormwater management ponds. The design method in this section assumes full exfiltration, e.g., removal of water from the base by infiltration into the underlying soil subgrade.

The catchment for permeable interlocking concrete pavement consists of the surface area of the pavement and an area that contributes runoff to it. A schematic cross-section and the design parameters are shown in Figure 17. The base is sized to store the runoff volume from the pavement area and the adjacent contributing areas.

Soil with infiltration rates or permeability less than 0.27 in./hr (2×10^{-6} m/sec) are generally silt loam, loam, sandy loam, loamy sand, and sand. Soils with lower permeability will limit the flow of water through the soil. They will require a high ratio of bottom surface area to storage volume. Therefore, careful consideration should be given to designing drain pipes to remove excess water in these situations.

The method described below does not provide guidance on drain pipe design within the base. This can be found in reference 35. Reference 36 includes methods for determining the diameter and spacing of pipes in open-graded bases for highway pavement drainage, as well as general guidance on pavement drainage design. This method accounts for monthly variations in the water generated from background flows in the soil and infiltration area, as well as that from the runoff from the

Climate	No Frost	No Frost	No Frost	No Frost	Frost	Frost	Frost	Frost
ESALs*	Soaked CBR Base Subbase	>15	10-14	5 to 9	Gravelly Soils	Clayey Gravels, Plastic Sandy Clays	Silty Gravel, Sand, Sandy Clays	Silts, Silty Gravel, Silty Clays
Pedestrian	No. 57 No. 2	4 (200) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)
50,000	No 57 No. 2	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	**
150,000	No. 57 No. 2	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 10 (250)	**
600,000	No. 57 No. 2	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 10 (250)	4 (100) 8 (200)	4 (100) 14 (350)	4 (100) 18 (450)	**

* ESALs = 18 kip (80 kN) Equivalent Single Axle Loads

** Strengthen subgrade with crushed-stone sub-base to full frost depth.

Notes:

1. All thicknesses are after compaction and apply to full, partial and no base exfiltration conditions.
2. Pedestrian applications should use a minimum base thickness of 10 in. (250 mm).
3. Thicknesses do not include No. 8 bedding course and permeable pavers.
4. Geotextile over the subgrade is optional.
5. Silty soils or others with more than 3% of particles smaller than 0.02 mm are considered to be frost susceptible.
6. All soils have a minimum CBR of 5%

Figure 18. Recommended minimum open-graded base and subbase thicknesses for permeable interlocking concrete pavements in inches (mm) (after ref. 37 and 38)

		Soil Subgrade Texture/Infiltration Rate Inches/Hour (m/sec)										
		Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Sandy Clay Loam	Clay Loam	Silty Clay Loam	Sandy Clay	Silty Clay	Clay
Criterion	T_s (hrs)	8.27 (6×10^{-5})	2.41 (2×10^{-5})	1.02 (7×10^{-6})	.52 (4×10^{-6})	.27 (2×10^{-6})	.17 (1×10^{-6})	.09 (6×10^{-7})	.06 (4×10^{-7})	.05 (3×10^{-7})	.04 (2×10^{-7})	.02 (10^{-7})
$f \times T_s/V_r$	24	496 (12.6)	145 (3.7)	61 (1.5)	31 (0.8)	16 (0.4)	10 (0.25)	5 (0.12)	4 (0.1)	3 (0.07)	2 (0.05)	1 (0.02)
for	48	992 (25.2)	290 (7.4)	122 (3.1)	62 (1.6)	32 (0.8)	20 (0.5)	11 (0.3)	7 (0.17)	6 (0.15)	2 (0.15)	2 (0.05)
(V_r=0.4)	72	1489 (37.8)	434 (11)	183 (4.6)	93 (2.4)	149 (1.2)	31 (0.8)	16 (0.9)	11 (0.13)	9 (0.2)	7 (0.17)	4 (0.1)

T_s = Maximum allowable storage time V_r = Voids ratio   ▨ = Lowest values unless base exfiltration is supplemented with drain pipes.

Figure 19. Maximum allowable depths, inches (m) of storage for selected maximum storage times (T_s in hours), minimum infiltration rates, inches/hours (m/sec)(31).

design storm. It does not include structural design for base thickness under vehicular traffic.

The Maryland method finds the maximum allowable depth of the pavement ($\mathbf{d}_{max}$) for a maximum storage time of 3 days. Shorter storage times are desirable to minimize risk of continually saturated and potentially weakened soil subgrade for areas subject to vehicular traffic. In that light, calculations should be done for 1 and 2 days, as well as 3 days, to compare differences in base thickness. In some instances, the calculated depth of the base for storage may be too shallow to support vehicular traffic. In these cases, the minimum base thickness would then be the depth required to accommodate traffic per Figure 18.

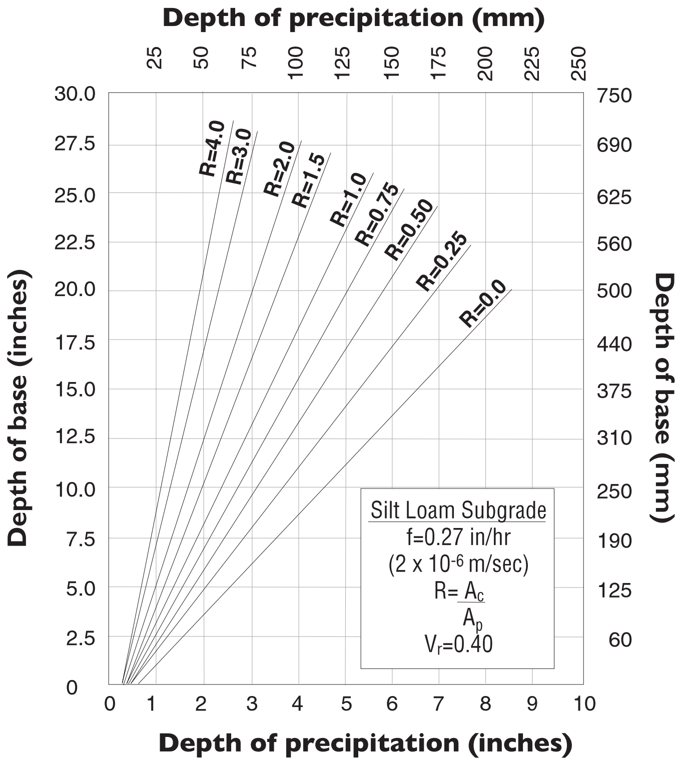


Figure 20. Open-graded base and subbase depth for silt loam subgrade.

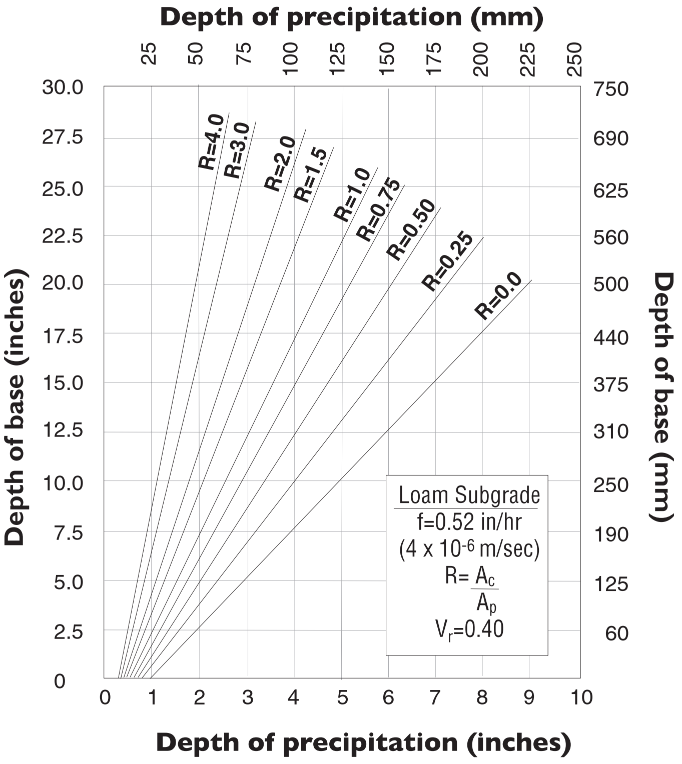


Figure 21. Open-graded base and subbase depth for loam subgrade.

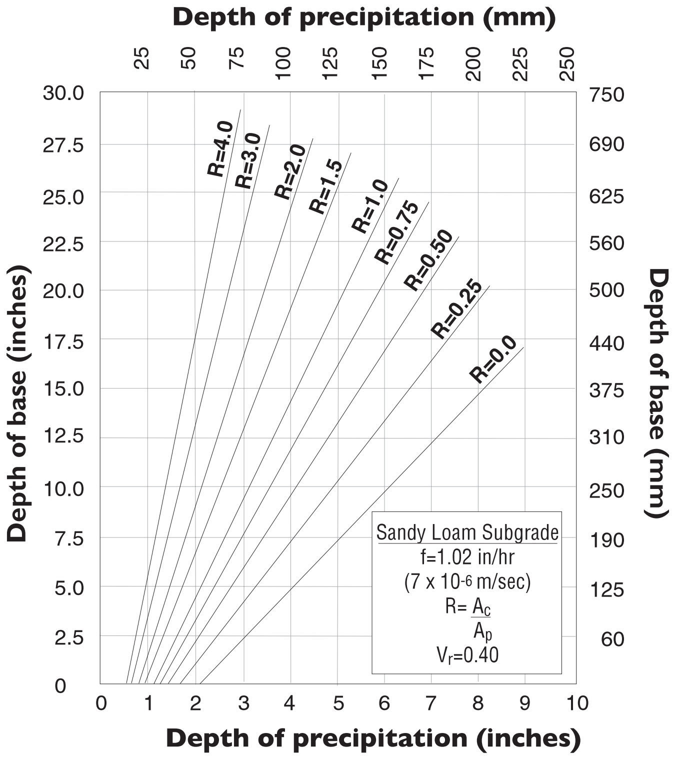


Figure 22. Open-graded base and subbase depth in sandy loam subgrade.

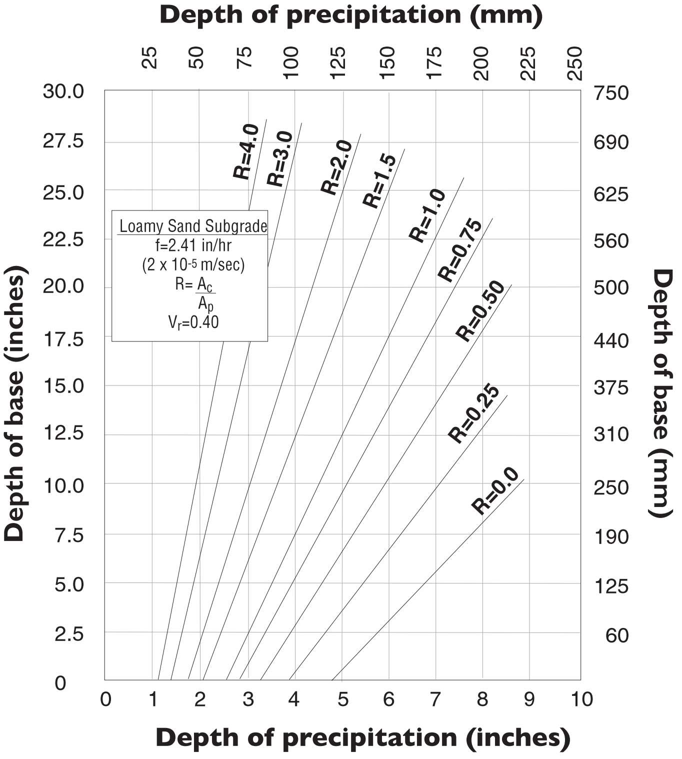


Figure 23. Open-graded base and subbase depth for loamy sand subgrade.

Note: In Figures 20 – 23 the CN = 98 of contribuitng areas

The values in Figure 18 are adopted from thickness designs for porous asphalt pavement (49) (50). Their use rests on the assumption that $3\frac{1}{8}$ in. (80 mm) thick concrete pavers provide a structural contribution similar to an equivalent thickness of porous asphalt, or an AASHTO layer coefficient of 0.4 per in. (25 mm) including the No. 8 bedding layer. The base thicknesses assume that the strength of the soil subgrade is at least 5% CBR (elastic modulus of 7,500 psi or 50 MPa).

The NRCS method typically uses 24-hour storm events as the basis for design. Therefore, this design method is based on controlling the increased runoff for a specific 24-hour storm. The specific duration and return period (e.g., 6-months, 1-year, 2-year, etc.) are provided by the locality. If the increase in peak discharge associated with the storm event cannot be managed, a first flush event should be the minimum selected for design.

For runoff storage, the maximum allowable base depth in inches (m) should meet the following criteria:

$$\mathbf{d_{max} = f \times T_s / V_r}$$

As shown in Figure 17, the design volume of water to be stored in the pavement base ($\mathbf{V_w}$) is:

	the runoff volume from the adjacent contributing area;	plus	the rainfall volume falling on the permeable pavement	minus	the exfiltration volume into the underlying soil
=	ΔQ_cA_c	+	PA_p	—	fTA_p

Values of **f** for infiltration rate should be obtained from Figure 19 for preliminary designs and checked against field tests for the infiltration rate of the soils.

For designs based on the Soil Conservation Service or NRCS Type II storm, the permeable pavement base filling time (**T**) is generally less than a 2-hour duration where the flow into the pavement exceeds the flow out of the pavement. Thus, a duration of 2 hours is used for **T**. The volume of water that must be stored ($\mathbf{V_w}$) may be defined as:

$$\mathbf{V_w = \Delta Q_c A_c + PA_p - fTA_p}$$

The volume of the stone base and subbase can also be defined in terms of its geometry:

$$\mathbf{V_p = V_w/V_r = d_pA_p}$$

Where:
$\mathbf{d_p}$ = the depth of the stone base (including subbase),
$\mathbf{A_p}$ = the permeable pavement surface area, and
$\mathbf{V_r}$ = the stone base and subbase void ratio (typically 0.4).

Setting the previous two equations equal will result in the following relationship:

$$\mathbf{d_pA_pV_r = \Delta Q_cA_c + PA_p - fTA_p} \qquad \text{(Equation 1)}$$

The surface area of the permeable pavement ($\mathbf{A_p}$) and the depth of the base ($\mathbf{d_p}$) can be defined in the following forms from the above equation:

$$\mathbf{A_p = \frac{\Delta Q_c A_c}{V_r d_p - P + fT}} \qquad \text{(Equation 2)}$$

and

$$\mathbf{d_p = \frac{\Delta Q_c R + P - fT}{V_r}} \qquad \text{(Equation 3)}$$

Where:
R = equal to the ratio of the contributing area and the permeable pavement area ($\mathbf{A_c/A_p}$).

Equation 3 will be used most often since the surface area of the pavement is normally known and the depth of the stone base is to be determined. All units in the above two equations are in terms of feet. Metric equivalents can be substituted.

The solution to Equation 3 is shown graphically in Figures 20 through 23. The graphs are based on storing the entire contributing area runoff volume ($\mathbf{Q_cA_c}$) based on the NRCS curve number for

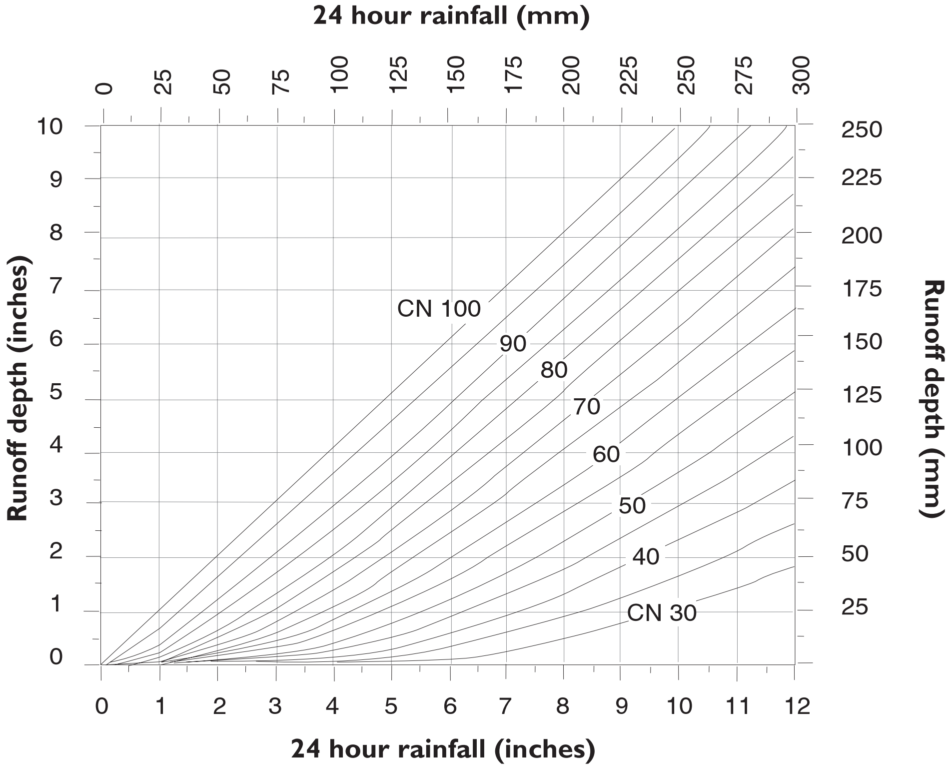


Figure 24. NRCS chart for finding runoff depth for various curve numbers.

an impervious area, CN = 98. The NRCS method offers a chart to assist in finding the depth of runoff from a given 24 hr. design storm for less than completely impervious areas, i.e., curve numbers lower than 98. This chart shown in Figure 24 is for 24-hour storms since many localities use this event for storm water management.

Design Procedure—There are two methods to design the base storage area. The first method computes the minimum depth of the base, given the area of the permeable pavement. This is called the *minimum depth method*. The other is compute the minimum surface area of the permeable pavement given the required design depth of the base. This is the *minimum area method*. The minimum depth method generally will be more frequently used.

Minimum Depth Method

1. From the selected design rainfall ($\mathbf{P}$) and the NRCS runoff curve number, compute the increased runoff volume from the contributing area ($\Delta \mathbf{Q}_c$).

2. Compute the depth of the aggregate base ($\mathbf{d}_p$) from Equation 3:

   Figures 20 through 23 may be used to determine the approximate stone base and subbase depth if the total runoff depth ($\mathbf{Q}_c$) is to be stored.

3. Compute the maximum allowable depth ($\mathbf{d}_{max}$) of the aggregate base and subbase by the feasibility formula:

$$\mathbf{d}_{max} = \mathbf{f} \times \mathbf{T}_s / \mathbf{V}_r$$

   where $\mathbf{d}_p$ must be less than or equal to $\mathbf{d}_{max}$ and at least 2 feet (0.6 m) above the seasonal high ground water table. If $\mathbf{d}_p$ does not satisfy this criteria, the surface area of the permeable pavement must be increased or a smaller design storm must be selected.

Minimum Area Method

1. From the selected design rainfall ($\mathbf{P}$) and the NRCS runoff curve number for the contributing area to be drained, compute the increased runoff depth from the contributing area ($\mathbf{DQ}_c$).

2. Compute the maximum allowable depth ($\mathbf{d_{max}}$) of the aggregate base from the feasibility formula:

$$d_{max} = f \times T_s / V_r$$

Select a design depth of the aggregate base ($\mathbf{d_p}$) less than or equal to $\mathbf{d_{max}}$ or the depth at least 2 feet (0.6 m) above the seasonal high ground water table, whichever is smaller.

3. Compute the minimum required surface area of the permeable interlocking concrete pavement ($\mathbf{A_p}$) from Equation 3:

$$A_p = \frac{\Delta Q_c A_c}{V_r d_p - P \times fT}$$

Design Example

Step 1—Assess site conditions. A parking lot is being designed in an urbanized area where storm sewers have limited capacity to convey runoff from an increase in existing impervious surfaces. Runoff from a 1 acre (4,047 m^2) asphalt parking lot (100% impervious: NRCS curve number or CN = 98) is to be captured by a 2 acre (8,094 m^2) permeable interlocking concrete pavement parking area over an open-graded base (R=0.5). The project is not close to building foundations nor are there any wells in the area. Soil borings revealed that the seasonal high water is 10 ft (3 m) below grade. The soil borings and testing indicated a USCS classification of SP (poorly-graded sandy soil) with 4% passing the No. 200 (0.075 mm) sieve. Permeability was tested at 1.02 in./hr (7×10^{-6} m/sec). While this was the tested permeability rate, the designer is taking a conservative position on design permeability by assuming it at half or 0.51 in./hr (0.0425ft/hr) (4×10^{-6} m/sec).This approach recognizes that there will be a loss of permeability from construction, soil compaction and clogging over time. The 96-hour soaked CBR of the soil is 12%. An estimated 300,000 ESALs will traffic this parking lot over 20 years. The pavers have an 8% or 0.08 open surface area. The site is in an area that receives frost.

Local regulations require this site to capture all runoff from a 2-year 24 hour storm. This is 5 in. (0.45 ft or 0.125 m) based on weather maps and local historical storm data. (Other localities often may require capturing the difference in runoff from before and after development for a given design storm or storms. A fairly rigorous requirement is given here of capturing all the runoff due to the limited capacity of the storm sewers. This is also done to simplify the design example.) This 5 inch depth meets the local water quality volume capture of 1.2 in. (30 mm) needed to meet pollutant reduction requirements.

The void space in the No. 57 open-graded, crushed stone base and No. 2 subbase provided by the local quarry is 40% or 0.40. A 1-day drainage of the base (or 24-hour drawdown) is the design criteria.

Step 2—Check the required permeability of the surface openings: 3 in./hr ÷ 0.08 = 37.5 in./hr (2.7×10^{-4} m/sec). This will require the use of No. 8 aggregate in the openings since the permeability of this material well exceeds 37.5 in./hr.

Since the area of the permeable interlocking concrete pavement parking lot is established, the depth of the base needs to be determined with the Minimum Depth Method

Step 3—Compute the increased runoff depth from the contributing area ($\Delta \mathbf{Q_c}$) from the selected design rainfall (**P**) and the NRCS runoff curve number.

Since the contributing area is impervious asphalt with a curve number = 98, all of the rainfall from design storm, or 5 in.(0.125 m), will flow from it into the permeable pavement. (See Figure 24).

Step 4—Compute the depth of the aggregate base ($\mathbf{d_p}$) **from Equation 3**:

$$d_p = \frac{\Delta Q_c R + P - fT}{V_r} = \frac{0.42 \text{ ft } (1 \text{ ac.}/2 \text{ ac.}) + 0.42 \text{ ft} - 0.0425 \text{ ft/hr } (2 \text{ hr}) = 1.36 \text{ ft } (0.4 \text{ m})}{0.4}$$

As a short cut, Figure 21 may be used to determine the approximate stone base depth if the total runoff depth ($\mathbf{Q_{cc}}$) is to be stored. Use this figure to find 16.3 in. or 1.36 ft (0.4 m).

Step 5—Compute the maximum allowable depth ($\mathbf{d_{max}}$) of the base by the feasibility formula:

$$\mathbf{d_{max} = f \text{ x } T_s / V_r}$$

where $\mathbf{d_p}$ must be less than or equal to $\mathbf{d_{max}}$ and at least 2 feet (0.6 m) above the seasonal high ground water table. If $\mathbf{d_p}$ does not satisfy this criteria, the surface area of the permeable pavement must be increased or a smaller design storm must be selected. The drainage time is 24 hours.

$$\mathbf{d_{max} = 0.0425 \text{ ft/hr x } 24 \text{ hr}/0.40 = 2.5 \text{ ft } (0.75 \text{ m})}$$

Step 6—Check the structural base thickness to be sure it has sufficient thickness to meet the storage requirements plus function as a base for 300,000 ESALs. The Frost Condition side of Figure 18 under sand with interpolation yields a thickness close to 18 in. (0.45 m). This is slightly thicker than what is required, 16.3 in. (0.4 m), to infiltrate and store the water in the base.

In no case should the structural thickness be reduced for the sake of economy. In some cases, the designer may wish to provide a thicker base due to expected heavy loads, or from spring thawing conditions that leave the soil completely saturated and weak. A frost protection layer of sand with drains can be placed under the base (separated by geotextiles) to reduce heave from highly susceptible soils in freeze-thaw conditions. This layer of sand offers additional filtering and reduction of pollutants, and construction details are discussed elsewhere.

It is very unlikely that the base and leveling courses will heave from ice. There is typically sufficient void space in them to allow frozen water to expand (9%) without heaving because it is rare that the base will be entirely and thoroughly saturated when freezing.

Step 7—Check to be sure the bottom of the base is at least 2 ft (0.6 m) from the seasonal high water table. The total thickness of the pavement will be:

3 1/8 in. (80 mm) thick concrete pavers
2 in. (50 mm) No. 8 stone leveling course
18 in. (450 mm); 4 in. (100 mm) No. 57 base and 14 in. (350 mm) No. 2 subbase
Total thickness = 23 in. (570 mm)

Approximately two feet (0.6 m) minus 10 ft (3 m) leaves 8 ft (2.4 m) to the top of the seasonal high water table. This is greater than the 2 ft (0.6 m) minimum distance required.

A somewhat hidden consideration is the storage capacity of the layer of No. 8 crushed stone. As a factor of safety, the void space in the No. 8 layer is not part of the storage calculations. This additional volume in the leveling course can serve as a safety buffer for storage in heavy rainfall.

Step 8—Check geotextile filter criteria. Sieve analysis of the soil subgrade showed that 4% passed the No. 200 (0.075 mm) sieve, and the gradation also showed the following:

	D_{10}	D_{15}	D_{50}	D_{60}	D_{85}
Soil subgrade	**0.10**	**0.12**	**0.25**	**0.32**	**0.63**

If geotextile is used the following criteria apply. FHWA geotextile filter criteria—For granular soils with ≤50% passing the No. 200 (0.075 mm) sieve, the following selection criteria is used for geotextiles taken from Figure 18.

All geotextiles: $\mathbf{AOS_{geotextile} \le B \text{ x } D_{85\,(soil)}}$

$$\mathbf{C_U = D_{60}/D_{10} = 0.32/0.10 = 3.2}$$

Where:

$\mathbf{B}$ = 1 for 2 $\ge \mathbf{C_U} \ge$ 8, 3.2 is okay.
$\mathbf{B}$ = 0.5 for 2 < $\mathbf{C_U}$ < 4, 3.2 is okay.
$\mathbf{B}$ = 8/$\mathbf{C_U}$ for 4 < $\mathbf{C_U}$ < 8

8/3.2 = 2.5 which does not satisfy 4 < 2.5 < 8. (Do not use for **B**.)

Figure 25. Curbing and drainage swale handle flows that exceed the design rainstorm.

Therefore, select a geotextile with an **AOS** (or **EOS**) between 0.5 x 0.63 = 0.32 mm and 1.0 x 0.63 = 0.63 mm.

Permeability criteria: k (fabric) ≥ k (0.52 in./hr)
Clogging criteria:
Woven: Percent of open area ≥ 4%
Nonwoven: Porosity ≥ 30%

AASHTO geotextile filter criteria (36)—For soils ≤ 50% passing the No. 200 (0.075 mm) sieve:

$$O_{95} < 0.59 \text{ mm } (AOS_{geotextile} \geq \text{No. 30 sieve})$$

The FHWA and AASHTO criteria provide similar guidance in selecting the **AOS** of a geotextile. In both cases, the **AOS** should be less than the No. 30 (0.600 mm) sieve, but greater than 0.32 mm.

NRCS Curve Numbers

Like most structural BMPs, the hydrological and pollution abatement characteristics of permeable interlocking concrete pavements should be incorporated into managing runoff within the large catchment, sub-watershed or watershed. The NRCS method is well-established, easy to use and easy to adapt to various BMPs. For example, reference 35 applies the NRCS method to infiltration trench design. For the permeable pavements themselves, the curve number can be estimated at 40 assuming a life-time design infiltration rate of 3 in./hr (75 mm/hr) with an initial abstraction of 0.2. This estimate applies to NRCS A hydrologic group soils. Users of other quantitative models (HEC-1, EPA SWMM, etc.) are encouraged to modify their programs to include permeable interlocking concrete pavements.

Some caution should be exercised in applying the NRCS method to calculating runoff in catchments as small as 5 acres (2 ha). This method is intended to calculate runoff from larger storms (2, 10, and 100 year return periods) with 24-hour durations. Therefore, the NRCS procedure tends to underestimate runoff from smaller storms in small drainage areas. Permeable interlocking concrete pavements control runoff from smaller storms. Typically, they generate the most amount of non-point water pollution. Claytor and Schueler suggest methods to calculate runoff from small areas from smaller storms especially when water quality needs to be controlled (9).

Rational Method Calculations

The NRCS method is commonly used for calculating runoff volumes and peak discharges. The Rational Method is only useful for estimating peak runoff discharges in watersheds up to 200 acres (80 ha). Peak flow is derived from the formula

$Q = CIA$
Where:
Q = peak discharge in cubic feet per second
I = design rainfall intensity in inches per hour
A = Drainage area in acres
C = Coefficient of runoff

Since the formula does not account for volume, *it cannot be used in water quality calculations.* For peak runoff calculations, the coefficient of runoff, C for the design life of interlocking concrete pavements can be estimated with the following formula: $C = \frac{I - \text{Design infiltration rate, in./hr}}{I}$

Protection Against Flooding From Extremely Heavy Rainstorms

There may be cases of extreme rainfall completely saturating the entire pavement structure. Drainage pipes should be built into the open-graded base to handle over-flow conditions. As an added measure of protection, there should be provision for an overflow area, by-pass or a drainage swale adjacent to the parking lot should it be completely saturated and flooded. An example of a drainage swale designed to handle overflows from an adjacent pervious parking lot is illustrated in Figure 25. Placing filter areas upslope from the pavement to reduce pollutants are recommended when space allows.

Cold Climate Design

The following design considerations apply to freezing climates with extended winters having large, rapid volumes of snow melt in the late winter and early spring. These areas are mostly in the northern U.S. and Canada (39).

1. Permeable interlocking concrete pavements should not be used in permafrost regions.
2. Chlorides and road abrasives (sand) can be concentrated in snowmelt. It's impossible for any best management practice, including permeable interlocking concrete pavements, to remove chlorides found in deicing materials. In addition, road sand can clog and reduce the infiltration capacity of these pavements. It is best to stockpile snow with chlorides and/or sand away from permeable interlocking concrete pavements. Possible locations include parking lot islands or bioretention areas.
3. If salts are used for deicing, then the groundwater should be monitored for chlorides. This can be done through sampling water in observation wells located in the pavement base and soil. Chloride levels in the samples should be compared to local or national criteria for the particular use of the water in the receiving lake, stream, or river (e.g., drinking water, recreation, fishing, etc.).
4. When the frost depth exceeds 3 ft. (1 m), all permeable parking lots should be set back from the subgrade of adjacent roads by at least 20 ft (6 m). This will reduce the potential for frost lenses and heaving of soil under the roadway.
5. Plowed snow piles and snow melt should not be directed to permeable interlocking concrete pavements if groundwater contamination from chlorides is a concern. However, this may not be avoidable in some situations. If high chloride concentrations in the runoff and groundwater are anticipated, then consideration should be given to using one or two design options below:
    (a) Runoff from snow melt can be diverted from the pavement during the winter. The diversion of runoff away from the pavement is typically through channels or pipes. Pipe

Pollutant Category Source	**Solids**	**Nutrients**	**Bacteria**	**Dissolved oxygen demands**	**Metals**	**Oils (PAHs)* SOCs***
Soil erosion	*	*		*	*	
Cleared vegetation	*	*		*		
Fertilizers		*				
Human waste	*	*	*	*		
Animal waste	*	*	*	*		
Vehicle fuels and fluids	*			*	*	*
Fuel combustion		*			*	
Vehicle wear	*			*	*	
Industrial/household chemicals	*	*	*	*	*	*
Industrial processes	*	*	*	*	*	*
Paints and preservatives				*	*	*
Pesticides				*	*	

PAHs = polynuclear aromatic hydrocarbons
SOCs = synthetic organic compounds

Figure 26. Common sources of pollution in urban stormwater runoff (3)

Pollutant	Infiltration Trench Design Type*			Infiltration Trenches & Porous Pavement
	0.5 in. (13 mm) of Runoff per Impervious acre	1.0 in. (25 mm) of Runoff per Impervious acre	2-year Design Storm Treatment	Median Pollutant Removal**
Total Suspended Solids	60-80%	80-100%	80-100%	95%
Total Phosphorous	40-60%	40-60%	60-80%	70%
Total Nitrogen	40-60%	40-60%	60-80%	51%
Biological Oxygen Demand	60-80%	60-80%	80-100%	—
Bacteria	60-80%	60-80%	80-100%	—
Metals	60-80%	60-80%	80-100%	99 (Zn)%

*Note: These rates are not based on actual data since monitoring what enters and leaves any infiltration facility is difficult to measure. These data are based on land application of pollutants and their treatment through soils.

**Actual monitored removal rates.

Figure 27. Projected average annual pollutant removal capability of infiltration areas in percent (from Debo and Reese (11) after Schueler) and actual, monitored removal rates documented by Winer (42)

valves must be operated each winter and spring. Snowmelt, however, is not treated but diverted elsewhere.

(b) Oversized drainage pipes can be used to remove the runoff during snowmelt, and then be closed for the remainder of the year.

The owner of the pavement must take responsibility for operating pipe valves that divert snowmelt. This may not be realistic with some designs.

6. Maintenance should include annual inspection in the spring and vacuum removal of surface sediment, as well as monitoring of groundwater for chlorides. This is paramount to continued infiltration performance.

Design for Control of Water Quality

Since urbanization significantly alters the land's capacity to absorb and process water pollutants, an increasing number of localities are regulating the amount of pollutants in stormwater. This is particulary the case when drinking-water supplies and fishing industries need to be protected. Urban stormwater pollutants and their sources are shown in Figure 26.

Permeable interlocking concrete pavements designed as an infiltration area over an open-graded base can reduce nonpoint source pollutants in storm water. Figure 27 illustrates the projected average annual pollutant removal capability of infilitration practices. Figure 27 demonstrates their effectiveness in reducing typical pollutants.

Keep in mind that the type of soil subgrade affects the pollution reduction capabilities of infiltration areas. Clay soils with a high cation exchange capacity will capture more pollutants than sandy soils. Debo and Reese (11) recommend that for control runoff quality, the storm water should infiltrate through at least 18 in. (0.45 m) of soil which has a minimum cation exchange capacity of 5 milliequivalents per 100 grams of dry soil. However, some clay soils that are effective pollutant filters do not have a sufficiently high infiltration rate or sufficient bearing capacity when saturated to be used under infiltration areas subject to vehicular loads.

Figure 28. Besides expected decreases in stormwater, runoff monitored from permeable interlocking concrete pavement projects such as Glen Brook Green Subdivision, Waterford, Connecticut in the Jordan Cove Watershed demonstrate substantial reductions of pollutants compared to those from conventional pavements.

Other approaches to reducing pollutants include filtering runoff from impervious areas through sand filters to help reduce sediment and oils. The typical application involves a small area that pretreats runoff prior to entering a detention or retention pond. The sand absorbs and helps treat the concentrated pollutants found in the first flush of a rainstorm. Sand filtering system design is found in reference 9.

The U.S. Environmental Protection Agency recognizes permeable interlocking concrete pavement as a BMP in reducing non-point source pollutants in runoff. In 2003 the U.S. EPA issued a New Development Management Measure for protection of coastal waters near urban areas (47). These measures appear in some non-coastal state and local BMP or stormwater design manuals.

Key measures require at least 80% reduction of total suspended solids (TSS) on an average annual basis, or post-development TSS loadings not exceeding predevelopment loadings. As part of that management measure for new development, to the extent practicable, post-development peak runoff rates and volumes should be similar to predevelopment levels based on rainfall from a 2-year, 24 hour storm. This helps reduce or prevent streambank erosion and scouring.

Permeable interlocking concrete pavement can achieve this reduction in peak flows and volumes. Regarding TSS reduction, several studies have demonstrated reductions at or near the 80% level:

- Rushton (48) monitored runoff and pollutants in a Tampa, Florida parking lot for two years. Eight sub-catchments included permeable pavement, concrete and asphalt pavement. Permeable pavement had the highest load removal efficiency for ammonia, nitrate, total nitrogen, total suspended solids, copper, iron, lead, manganese and zinc. Most removal rates exceeded 75%.
- Bean (49) compared runoff quantities and quality over 18 months from a small asphalt and permeable interlocking concrete pavement parking lot with an open-graded aggregate base at a bakery in Goldsboro, North Carolina. The study summarizes the statistical mean pollutant concentrations from 14 rainstorms and illustrates substantial pollutant reductions including 75% for TSS.
- Scholes (50) reports on pollutant removal efficiencies of various BMPs in the United Kingdom and identifies permeable paving has having an average of 82% removal efficiency with data ranging between 64% and 100% removal rates.
- Clausen (51) monitored runoff from driveways for one year in a small residential subdivision in Waterford, Connecticut. The driveways consisted of asphalt, crushed stone and permeable interlocking concrete pavement (over a dense-graded base). Annual pollutant export in kg/ha/yr was 86% lower on the paver driveways than on the asphalt ones.
- James (52) examined surface runoff from nine rainstorms over four months from asphalt, concrete pavers and permeable interlocking concrete pavers. He also measured pollutants in

> the base and subbase of the permeable pavement. Permeable interlocking concrete pavements rendered a 97% reduction of total suspended solids compared to that generated by the asphalt surface. Similar differences were indicated by solids sampled in water leaving the permeable pavement subbase.

Permeable interlocking concrete pavements clearly improve water quality by capturing and filtering runoff from most commonly occurring storms. These are the ones with the highest concentration of pollutants. Some localities require capturing a given volume or depth of rainfall to reduce pollutants such as total suspended solids and nutrients such as phosphorous. A method for estimating the amount of water to treat or "water quality capture volume" has been developed by the Water Environment Federation in WEF Manual of Practice No. 23, *Urban Runoff Quality Management* (pages 175-178). The Manual also provides BMP selection and design guidance (53).

The WEF method can be used to calculate the base water storage requirements needed for permeable interlocking concrete pavements to help ensure pollutant treatment. Estimated stormwater quantity storage volumes required by the locality should be compared to the water volume that needs to be captured and treated for improving water quality. In most cases, water volume captured to control stormwater quantities will exceed the volume needed to be captured and treated for improved water quality. In such cases, the water volume captured to improve water quality is automatically included in the water quantity calculations for the design storm.

Section 3. Construction

Reducing Clogging

Preventing and diverting sediment from entering the base and pavement surface during construction ***must be the highest priority***. Extra care must be applied to keeping sediment completely away from the area. Simple practices such as keeping muddy construction equipment away from the area, installing silt fences, staged excavation, and temporary drainage swales that divert runoff away from the area will make the difference between a pavement that infiltrates well or poorly. Moreover, the pavement should not receive runoff until the entire contributing drainage area is stabilized. This should be included in the construction drawings and specifications.

One technique for reducing silting and clogging of soil during construction is to excavate the base within 6 in. (150 mm) of the final bottom elevation. This area can contain water during storms over the construction period and drain via temporary drain pipes. Heavy equipment should be kept from this area to prevent compaction. If equipment needs to traverse the bottom of the excavation, tracked vehicles can reduce the risk of soil compaction. As the project progresses, sediment and the remaining soil depth can be excavated to the final grade prior to installing the subbase and base stone. Depending on the project design, this technique might eliminate the need for a separate sediment basin during construction.

Preventing and diverting sediment from entering the base and pavement surface during construction must be the **highest** priority.

Soil Compaction

If the initial undisturbed soil infiltration can be maintained during excavation and construction, there is a high probability that the base will drain as designed. If the soil is inadvertently compacted by equipment during construction, there will be a substantial loss of infiltration. A loss is acceptable if the infiltration rate of the soil *when compacted* was initially considered during design and in drainage calculations.

Compaction of low CBR soils (<4%) may be necessary to attain sufficient structural support and to minimize rutting from vehicular traffic. These soils should be compacted to at least 95% of standard Proctor density. Drains in the open-graded base will likely be required to remove water since compaction will greatly reduce the soil's permeability.

Geotextiles

Geotextiles are used in some permeable pavement applications and are optional when using a No. 2 aggregate subbase. Specifications and minimum physical requirements for geotextiles for separation and drainage can be found in reference 26 by AASHTO Task Force 25. For vehicular applications, high-quality fabric should be specified that resists the puncturing by coarse, angular aggregate from compaction during construction and from repeated wheel loads during its service life. Bases should have their sides and bottoms wrapped in geotextile. Overlap recommendations are provided in AASHTO specifications. ICPI recommends a minimum of 1 ft (1.3 m) overlap in well-drained soils and 2 ft (0.6 m) overlap on poor-draining weaker soils (CBR<5%).

Handling Excess Water

Designs should have curb cut-outs and/or catch basins to handle emergency overflow conditions. Partial or no exfiltration designs require pipes to handle storage and outflow from design storms and those from overflow conditions. The size and placement of drain pipes should be determined by a civil engineer experienced in hydrological design and stormwater management. Pipes in bases subject to traffic should withstand repeated vehicular loads.

Perforations in pipes should be $^3/_8$ in. (10 mm) in diameter and terminate 1 ft (0.3 m) short of the sides of the opening for the base. When corrugated metal drain pipes are used, they should be aluminized, and aluminized pipe in contact with concrete should be coated to prevent corrosion. Perforated metal drain pipes should have caps fastened to the ends.

A 6 in. (150 mm) diameter vertical perforated pipe that serves as an observation well is recommended in all pavements. The pipe should be kept vertical during filling of the excavated area with open-graded aggregate and during compaction. The bottom of the pipe can be attached to a plate for stability when resting on the geotextile and held in place during base filling and compaction by

Figure 29. Mechanized equipment placing permeable pavers at a rate as high as three times greater than manual methods. This project is a parking lot.

first placing some open graded aggregate on the plate. The bottom of the pipe should be capped. It should be located in the most downslope position and a minimum of 3 ft. (1 m) from the sides of the base.

Open-graded Aggregate Bases

No. 2 subbase material should be spread in 4 to 6 in. (100 to 150 mm) lifts and compacted with a static roller. At least 4 passes should be made with a minimum 10 ton (9 T) steel drum roller. The No. 57 base layer can be spread and compacted as one 4 in. (100 mm) lift. These stone materials should be moist during compaction.

The initial passes with the roller can be with vibration to consolidate the base material. The final passes should be without vibration. A test section of the base should be constructed and closely monitored during compaction. The section will indicate settlement of the pavement section, and whether crushing of the aggregate is excessive. The area should be used to train construction personnel on these and related aspects.

When all lifts are compacted the surface should then be topped with a 2 in. (50 mm) thick layer of moist No. 8 crushed stone. This layer of finer crushed stone is screeded and leveled over the No. 57 base. The No. 8 should be moist to facilitate movement into the No. 57. The surface tolerance of the screeded No. 8 material should be ±$^{1}/_{2}$ in. over 10 ft. (±13 mm over 3 m).

The concrete pavers should be placed immediately after the No. 8 base bedding is placed and screeded. Construction equipment and foot traffic should be kept off the screeded layer. When riding on the No. 2 subbase and the No. 57 base equipment drivers should avoid rapid acceleration, hard braking, or sharp turning on the compacted layers. Tracked equipment is recommended. If the base surfaces are disturbed, they should be releveled and recompacted.

Stabilized Bases

Open-graded bases may be stabilized with asphalt or cement prior to placement. Stablilize the base and subbase layer and not the No. 8 layer used for bedding. The use of asphalt will likely reduce the storage capacity of the base, but stabilization may be necessary to increase its structural capacity. To maintain high void space, only enough asphalt to coat the aggregate is required. For further information on the design and construction of asphalt bases, see reference 40.

Likewise, cement should be applied only to coat the aggregate for the base, and care should be taken not to fill the voids with excess paste. The water-cement ratio should be controlled to make a paste that coats the aggregate.

Edge Restraints

Recommended edge restraints for permeable interlocking concrete pavements on open-graded bases are cast-in-place and precast concrete curbs. They should be a minimum of 6 in. (150 mm) wide and 12 in. (300 mm) deep. Consideration should be given to providing a stable footer or concrete haunch under the curbs. Plastic edge restraints that utilize spikes are not recommended for commercial and municipal applications.

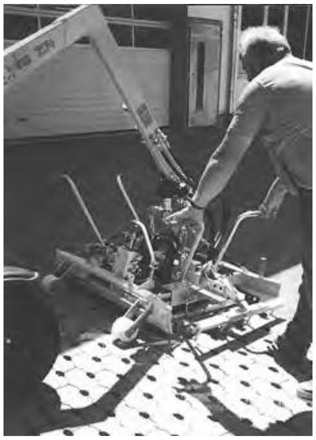


Figure 30. Interlocking shapes installed by machine.

Paver Installation

Figure 31. Mechanized placement of pavers with wide joints.

After screeding the bedding material, the pavers are placed on this screeded layer joints filled with No. 8 stone, the surface swept clean and compacted with a plate compactor. For units 3$^1/_8$ to 4 in. (80 to 100 mm) thick, the plate compactor should exert a minimum 4,000 lbf (8 kN) at 75 to 90 Hz. For units thicker than 4 in. (100 mm), the compactor should exert at least 6,800 lbf (30 kN). After initial compaction, the joints or openings are filled with No. 8 material, the paver surface swept clean and the paving units are compacted again. For vehicular areas, proof rolling is recommended with at least two passes of a 10 T rubber-tired roller.

Paver installation can be by hand or with mechanical equipment. Mechanized installation may be a cost-efficient means to install the units and will reduce the installation time. Figure 29 shows mechanized equipment placing permeable pavers for a parking lot adjacent to a baseball field. Figure 30 shows placement of another interlocking shape, while Figure 31 illustrates mechanized placement of pavers with widened joints. For further information on mechanical installation, consult ICPI *Tech Spec 11—Mechanical Installation of Interlocking Concrete Pavements* (41) and ICPI *Tech Spec 15—A Guide for the Construction of Mechanically Installed Interlocking Concrete Pavements* (54).

Units should be cut to fill any spaces along the edges prior to compaction. Cut units should be no smaller than one-third of a whole unit if subject to vehicular traffic. All installed units should be compacted into the No. 8 aggregate and joints filled with the appropriate material and pavers compacted again within 6 ft (2m) of the laying face at the end of each day.

Section 4. Guide Specifications and Construction Checklist

SECTION 32 14 13.19 PERMEABLE INTERLOCKING CONCRETE PAVEMENT (1995 MasterFormat Section 02795)

Note: This guide specification describes construction of permeable interlocking concrete pavers on a permeable, open-graded crushed stone bedding layer (typically No. 8 stone). This layer is placed over an open-graded base (typically No. 57 stone) and sub-base (typically No. 2 stone). The pavers and bedding layer are placed over an open-graded crushed stone base with exfiltration to the soil subgrade. In low infiltration soils or installations with impermeable liners, some or all drainage is directed to an outlet via perforated drain pipes in the subbase. While this guide specification does not cover excavation, liners and drain pipes, notes are provided on these aspects.

The text must be edited to suit specific project requirements. It should be reviewed by a qualified civil or geotechnical engineer, or landscape architect familiar with the site conditions. Edit this specification term as necessary to identify the design professional in the General Conditions of the Contract.

PART 1 GENERAL

1.01 SUMMARY

A. Section Includes
   1. Permeable interlocking concrete pavers.
   2. Crushed stone bedding material.
   3. Open-graded subbase aggregate.
   4. Open-graded base aggregate.
   5. Bedding and joint/opening filler materials.
   6. Edge restraints.
   7. [Geotextiles].

B. Related Sections
   1. Section[_______]: Curbs.
   2. Section[_______]: [Stabilized] aggregate base.
   3. Section[_______]: [PVC] Drainage pipes
   4. Section[_______]: Impermeable liner.
   5. Section[_______]: Edge restraints.
   6. Section[_______]: Drainage pipes and appurtenances.
   7. Section[_______]: Earthworks/excavation/soil compaction.

1.02 REFERENCES

A. American Society for Testing and Materials (ASTM)
   1. C 67, Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units.
   2. C 131, Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.
   3. C 136, Method for Sieve Analysis for Fine and Coarse Aggregate.
   4. C 140, Test Methods for Sampling and Testing Brick and Structural Clay Tile, Section 8 – Freezing and Thawing.
   5. D 448, Standard Classification for Sizes of Aggregate for Road and Bridge Construction.
   6. C 936, Standard Specification for Solid Interlocking Concrete Pavers.
   7. C 979, Specification for Pigments for Integrally Colored Concrete.

8. D 698, Test Methods for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using a 5.5-lb (2.49 kg) Rammer and 12 in. (305 mm) drop.
9. D 1557, Test Methods for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using a 10-lb (4.54 kg) Rammer and 18 in. (457 mm) drop.
10. D 1883, Test Method for California Bearing Ratio of Laboratory-Compacted Soils.
11. D 4254, Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density.

B. Canadian Standards Association (CSA)
    1. A231.2 Precast Concrete Pavers

C. Interlocking Concrete Pavement Institute (ICPI)
    1. Permeable Interlocking Concrete Pavement manual.

1.03 SUBMITTALS

A. In accordance with Conditions of the Contract and Division 1 Submittal Procedures Section.

B. Manufacturer's drawing and details: Indicate perimeter conditions, junction with other materials, expansion and control joints, paver [layout,] [patterns,] [color arrangement,] installation [and setting] details. Indicate layout, pattern, and relationship of paving joints to fixtures and project formed details.

C. Minimum 3 lb (2 kg) samples of subbase, base and bedding aggregate materials.

D. Sieve analysis of aggregates for subbase, base and bedding materials per ASTM C 136.

E. Soils report indicating density test reports, classification, and infiltration rate measured on-site under compacted conditions, and suitability for the intended project.

F. Erosion and sediment control plan.

G. [Stormwater management (quality and quantity) calculations.]

H. Permeable concrete pavers:
    1. Manufacturer's product catalog sheets with specifications.
    2. [Four] representative full-size samples of each paver type, thickness, color, and finish. Submit samples indicating the range of color expected in the finished installation.
    3. Accepted samples become the standard of acceptance for the work of this Section.
    4. Laboratory test reports certifying compliance of the concrete pavers with ASTM C 936 [CSA A31.2].
    5. Manufacturer's material safety data sheets for the safe handling of the specified materials and products.
    6. Manufacturer's written quality control procedures including representative samples of production record keeping that ensure conformance of paving products to the project specifications.

H. Paver Installation Subcontractor:
    1. A copy of Subcontractor's current certificate from the Interlocking Concrete Pavement Institute Concrete Paver Installer Certification program.
    2. Job references from projects of a similar size and complexity. Provide Owner/Client/General Contractor names, postal address, phone, fax, and email address.
    3. Written Method Statement and Quality Control Plan that describes material staging and flow, paving direction and installation procedures, including representative reporting forms that ensure conformance to the project specifications.

1.04 QUALITY ASSURANCE

A. Paver Installation Subcontractor Qualifications:
    1. Utilize an installer having successfully completed concrete paver installation similar in design, material and extent indicated on this project.
    2. Utilize an installer holding a current certificate from the Interlocking Concrete Pavement Institute Concrete Paver Installer Certification program.

B. Regulatory Requirements and Approvals: [Specify applicable licensing, bonding or other requirements of regulatory agencies.].

C. Review the manufacturers' quality control plan, paver installation subcontractor's Method Statement and Quality Control Plan with pre-construction meeting of representatives from the manufacturer, paver installation subcontractor, general contractor, engineer and/or owner's representative.

C. Mock-Ups:
  1. Install a 10 ft x 10 ft (3 x 3 m) paver area.
  2. Use this area to determine surcharge of the bedding layer, joint sizes, lines, laying pattern(s), color(s) and texture of the job.
  3. This area will be used as the standard by which the work will be judged.
  4. Subject to acceptance by owner, mock-up may be retained as part of finished work.
  5. If mock-up is not retained, remove and properly dispose of mock-up.

1.05 DELIVERY, STORAGE, AND HANDLING

A. General: Comply with Division 1 Product Requirement Section.
B. Comply with manufacturer's ordering instructions and lead-time requirements to avoid construction delays.
C. Delivery: Deliver materials in manufacturer's original, unopened, undamaged container packaging with identification tags intact on each paver bundle.
  1. Coordinate delivery and paving schedule to minimize interference with normal use of buildings adjacent to paving.
  2. Deliver concrete pavers to the site in steel banded, plastic banded, or plastic wrapped cubes capable of transfer by forklift or clamp lift.
  3. Unload pavers at job site in such a manner that no damage occurs to the product or existing construction
D Storage and Protection: Store materials in protected area such that they are kept free from mud, dirt, and other foreign materials.

1.06 ENVIRONMENTAL REQUIREMENTS

A. Do not install in rain or snow.
B. Do not install frozen bedding materials.

1.07 MAINTENANCE

A. Extra materials: Provide [Specify area] [Specify percentage] additional material for use by owner for maintenance and repair.
B. Pavers shall be from the same production run as installed materials.

PART 2 PRODUCTS

Note: Some projects may include permeable and solid interlocking concrete pavements. Specify each product as required.

2.01 PERMEABLE INTERLOCKING CONCRETE PAVERS

A. Manufacturer: [Specify ICPI member manufacturer name.].
  1. Contact: [Specify ICPI member manufacturer contact information.].
B. Permeable Interlocking Concrete Paver Units:
  1. Paver Type: [Specify name of product group, family, series, etc.].
    a. Material Standard: Comply with ASTM C 936 [CSA A231.2].
    b. Color [and finish]: [Specify color.] [Specify finish].
    c. Color Pigment Material Standard: Comply with ASTM C 979.

Note: Concrete pavers may have spacer bars on each unit. Spacer bars are recommended for mechanically installed pavers. Manually installed pavers may be installed with or without spacer bars. Verify with manufacturers that overall dimensions do not include spacer bars.

d. Size: [Specify.] inches [({Specify.}mm)] x [Specify.] inches [({Specify}mm)] x [Specify.] inches [({Specify.} mm)] thick.

Note: When 3^1/$_8$ in. (80 mm) thick pavers are specified, their compressive strength test results per ASTM C 140 should be adjusted by multiplying by 1.18 to equate the results to that from 2^3/$_8$ in. (60 mm) thick pavers.

2.02 PRODUCT SUBSTITUTIONS

A. Substitutions: No substitutions permitted.

2.03 CRUSHED STONE FILLER, BEDDING, BASE AND SUBBASE

A. Crushed stone with 90% fractured faces, LA Abrasion < 40 per ASTM C 131, minimum CBR of 80% per ASTM D 1883.
B. Do not use rounded river gravel.
C. All stone materials shall be washed with less than 1% passing the No. 200 sieve.
D. Joint/opening filler, bedding, base and subbase: conforming to ASTM D 448 gradation as shown in Tables 1, 2 and 3 below:

Note: No. 89 or finer gradation may be used to fill permeable pavers with narrow joints.

Table 1
Grading Requirements for ASTM No. 8 Bedding and Joint/Opening Filler

Sieve Size	Percent Passing
12.5 mm (1/2 in.)	100
9.5 mm (3/8 in.)	85 to 100
4.75 mm (No. 4)	10 to 30
2.36 mm (No. 8)	0 to 10
1.16 mm (No. 16)	0 to 5

Table 2
Grading Requirements for ASTM No. 57 Base

Sieve Size	Percent Passing
37.5 mm (1 1/2 in.)	100
25 mm (1 in.)	95 to 100
12.5 mm (1/2 in.)	25 to 60
4.75 mm (No. 4)	0 to 10
2.36 mm (No. 8)	0 to 5

Table 3
Grading Requirement for ASTM No. 2 Subbase

Sieve Size	Percent Passing
75 mm (3 in.)	100
63 mm (2 1/2 in.)	90 to 100
50 mm (2 in.)	35 to 70
37.5 mm (1 1/2 in.)	0 to 15
19 mm (3/4 in.)	0 to 5

E. Gradation criteria for the bedding and base:

Note: Dx is the particle size at which x percent of the particles are finer. For example, D15 is the particle size of the aggregate for which 15% of the particles are smaller and 85% are larger.

1. D15 base stone /D50 bedding stone < 5.
2. D50 base stone/D50 bedding stone > 2.

2.04 ACCESSORIES

A. Provide accessory materials as follows:

Note: Curbs will typically be cast-in-place concrete or precast set in concrete haunches. Concrete curbs may be specified in another Section. Do not use plastic edging with steel spikes to restrain the paving units.

1. Edge Restraints
   - a. Manufacturer: [Specify manufacturer.].
   - b. Material: [Pre-cast concrete] [Cut stone] [Concrete].
   - b. Material Standard: [Specify material standard.].

Note: See ICPI publication, Permeable Interlocking Concrete Pavements for guidance on geotextile selection. Geotextile use is optional.

2. Geotextile Fabric:
   - a. Material Type and Description: [Specify material type and description.].
   - b. Material Standard: [Specify material standard.].
   - c. Manufacturer: [Acceptable to interlocking concrete paver manufacturer]]

PART 3 EXECUTION

3.01 ACCEPTABLE INSTALLERS

A. [Specify acceptable paver installation subcontractors.].

3.02 EXAMINATION

Note: The elevations and surface tolerance of the soil subgrade determine the final surface elevations of concrete pavers. The paver installation contractor cannot correct deficiencies excavation and grading of the soil subgrade with additional bedding materials. Therefore, the surface elevations of the soil subgrade should be checked and accepted by the General Contractor or designated party, with written certification presented to the paver installation subcontractor prior to starting work.

A. Acceptance of Site Verification of Conditions:

1. General Contractor shall inspect, accept and certify in writing to the paver installation subcontractor that site conditions meet specifications for the following items prior to installation of interlocking concrete pavers.

Note: Compaction of the soil subgrade should be determined by the project engineer. If the soil subgrade requires compaction, compact to a minimum of 95% standard Proctor density per ASTM C 698. Compacted soil density and moisture should be checked in the field with a nuclear density gauge or other test methods for compliance to specifications. Stabilization of the soil and/or base material may be necessary with weak or continually saturated soils, or when subject to high wheel loads. Compaction will reduce the permeability of soils. If soil compaction is necessary, reduced infiltration may require drain pipes within the open-graded sub base to conform to local storm drainage requirements.

   - a. Verify that subgrade preparation, compacted density and elevations conform to specified requirements.
   - b. Provide written density test results for soil subgrade to the Owner, General Contractor and paver installation subcontractor.
   - c. Verify location, type, and elevations of edge restraints, [concrete collars around] utility structures, and drainage pipes and inlets.

2. Do not proceed with installation of bedding and interlocking concrete pavers until subgrade soil conditions are corrected by the General Contractor or designated subcontractor.

3.03 PREPARATION

A. Verify that the soil subgrade is free from standing water.
B. Stockpile joint/opening filler, base and subbase materials such that they are free from standing water, uniformly graded, free of any organic material or sediment, debris, and ready for placement.
C. Edge Restraint Preparation:
    2. Install edge restraints per the drawings [at the indicated elevations].

3.04 INSTALLATION

Note: The minimum slope of the soil subgrade should be 0.5%. Actual slope of soil subgrade will depend on the drainage design and exfiltration type. All drainpipes, observation wells, overflow pipes, geotextile (if applicable) and impermeable liner (if applicable) should be in place per the drawings prior to or during placement of the subbase and base, depending on their location.

Care must be taken not to damage drainpipes during compaction and paving. No mud or sediment can be left on the base or bedding aggregates. If they are contaminated, they must be removed and replaced with clean materials.

A. General
    1. Any excess thickness of soil applied over the excavated soil subgrade to trap sediment from adjacent construction activities shall be removed before application of the [geotextile] and subbase materials.
    2. Keep area where pavement is to be constructed free from sediment during entire job. [Geotextiles] Base and bedding materials contaminated with sediment shall be removed and replaced with clean materials.
    3. Do not damage drainpipes, overflow pipes, observation wells, or any inlets and other drainage appurtenances during installation. Report any damage immediately to the project engineer.
B. Geotextiles
    1. Place on [bottom and] sides of soil subgrade. Secure in place to prevent wrinkling from vehicle tires and tracks.
    2. Overlap a minimum of [0.3 in (12 in.)] [0.6 m (24 in.)] in the direction of drainage.
C. Open-graded subbase and base
    1. Moisten, spread and compact the No. 2 subbase in 100 to 150 mm (4 to 6 in.) lifts [without wrinkling or folding the geotextile. Place subbase to protect geotextile from wrinkling under equipment tires and tracks.]
    1. For each lift, make at least two passes in the vibratory mode then at least two in the static mode with a minimum 10 T (10 t) vibratory roller until there is no visible movement of the No. 2 stone. Do not crush aggregate with the roller.
    2. The surface tolerance of the compacted No. 2 subbase shall be ±65mm (±2$^1/_2$ in.) over a 3 mm (10 ft.) straightedge.
    3. Moisten, spread and compact No. 57 base in 100 mm (4 in.) lift over the compacted No. 2 subbase with a minimum 10 T (10 t) vibratory roller until there is no visible movement of the No. 57 stone. Do not crush aggregate with the roller.
    4. The surface tolerance the compacted No. 57 base should not deviate more than. ±25 mm (±1 in.) over a 3 m (10 ft.) straightedge.

Note: In-place density of the base and subbase may be checked per ASTM D 4254. Compacted density should be 95% of the laboratory index density established for the subbase and base stone.

D. Bedding layer
    a. Moisten, spread and screed the No. 8 stone bedding material.
    b. Fill voids left by removed screed rails with No. 8 stone.
    c. The surface tolerance of the screeded No. 8 bedding layer shall be ±10 mm ($^3/_8$ in.) over a 3 m (10 ft) straight-edge.
    d. Do not subject screeded bedding material to any pedestrian or vehicular traffic before paving unit installation begins.

E. Permeable interlocking concrete pavers and joint/opening fill material

d. Lay the pavers [paving slabs] in the pattern(s) and joint widths shown on the drawings. Maintain straight pattern lines.
e. Fill gaps at the edges of the paved area with cut units. Cut pavers subject to tire traffic shall be no smaller than 1/3 of a whole unit.
f. Cut pavers and place along the edges with a [double-bladed splitter or] masonry saw.
g. Fill the openings and joints with [No. 8] stone.

Note: Some paver joint widths may be narrow and not accept most of the No. 8 stone. Use joint material that will fill joints such as washed ASTM No. 9 or No. 10 stone. These smaller stone sizes are recommended for filling joints in pedestrian applications that use $2^{3}/_{8}$ in. (60 mm) thick pavers.

h. Remove excess aggregate on the surface by sweeping pavers clean.
i Compact and seat the pavers into the bedding material using a low-amplitude, 75-90 Hz plate compactor capable of at least 18 kN (4,000 lbs.) centrifugal compaction force. This will require at least two passes with the plate compactor.
j. Do not compact within 2 m (6 ft) of the unrestrained edges of the paving units.
k. Apply additional aggregate to the openings and joints, filling them completely. Remove excess aggregate by sweeping then compact the pavers. This will require at least two passes with the plate compactor.
l. All pavers within 2 m (6 ft) of the laying face must be left fully compacted at the completion of each day.
m. The final surface tolerance of compacted pavers shall not deviate more than ±10 mm ($\pm^{3}/_{8}$ in.) under a 3 m (10 ft) long straightedge.
n. The surface elevation of pavers shall be 3 to 6 mm ($^{1}/_{8}$ to $^{1}/_{4}$ in.) above adjacent drainage inlets, concrete collars or channels.

3.05 FIELD QUALITY CONTROL

A. After sweeping the surface clean, check final elevations for conformance to the drawings.
B. Lippage: No greater than 3 mm ($^{1}/_{8}$ in.) difference in height between adjacent pavers.

Note: The minimum slope of the finished pavement surface should be 1%. The surface of the pavers may be 3 to 6 mm ($^{1}/_{8}$ to $^{1}/_{4}$ in.) above the final elevations after compaction. This helps compensate for possible minor settling normal to pavements.

C. The surface elevation of pavers shall be 3 to 6 mm ($^{1}/_{8}$ to $^{1}/_{4}$ in.) above adjacent drainage inlets, concrete collars or channels.

3.06 PROTECTION

A. After work in this section is complete, the General Contractor shall be responsible for protecting work from sediment deposition and damage due to subsequent construction activity on the site.

END OF SECTION

Construction Inspection Checklist

Pre-excavation

☐ Roped off area to divert construction vehicles
☐ Runoff diverted: no runoff enters pavement from disturbed areas
☐ No runoff enters pavement until soils stabilized in area draining to permeable pavement
☐ Utilities located and marked
☐ Marked area to be excavated
☐ Walk through with builder/contractor/subcontractor to review Erosion and Sediment Control Plan

Excavation

☐ Size and location conforms to plan
☐ At least 10 ft (3 m) from foundation walls
☐ At least 100 ft (30 m) from water supply wells
☐ Soil permeability: no sealed surfaces, rocks and roots removed, voids refilled with permeable soil
☐ Soil compacted to specifications and field tested with density measurements
☐ Groundwater/bedrock: no groundwater seepage, standing water, or presence of bedrock

Geotextile

☐ Meets specifications
☐ Placement and downslope overlap (typically 2 ft or 0.6 m) conform to specifications and drawings
☐ Sides of excavation covered with geotextile
☐ No tears or holes
☐ Minimal wrinkles, pulled taught and staked

Drain pipes/observations wells

☐ Size, perforations, locations, slope, and outfalls meet specifications and drawings
☐ Elevation of overflow pipes correct

Aggregate base and subbase courses

☐ Sieve analysis conforms to specifications
☐ Laid or spread (not dumped) with a front-end loader to avoid aggregate segregation
☐ Thickness, placement, and compaction meets specifications and drawings

Aggregate choke course

☐ Sieve analysis conforms to specifications
☐ Laid or spread (not dumped) from a front-end loader to avoid aggregate segregation
☐ Thickness, placement, and compaction meet specifications and drawings
☐ Geotextile applied under bedding sand (if used)

Edge restraints

☐ Elevation, placement, and materials meet specifications and drawings

Permeable interlocking concrete pavers

☐ Meets ASTM or CSA standards as applicable
☐ Elevations, slope, laying pattern, joint spacers, and placement/compaction meet drawings and specifications
☐ Joint materials conform to specifications (aggregate or sand/topsoil/grass)
☐ Drainage swales or storm sewer inlets for emergency overflow
☐ Pre-treatment drainage area for filtering runoff

Final inspection

☐ Elevations and slope conform to drawings
☐ Transitions to impervious paved areas separated with edge restraints
☐ Stabilization of soil in area draining into permeable pavement (min. 20 ft (6 m) vegetative strip recommended)
☐ Upslope sand filter(s) operational.

Section 5. Maintenance

Figure 32. Unwanted sediment tracked onto permeable pavers via this gravel access ramp to a construction site will clog their openings.

Permeable interlocking concrete pavements can become clogged with sediment over time, thereby slowing their infiltration rate and decreasing storage capacity. Figure 32 shows an installation subject to nearby construction that has brought sediment into pavement openings. Clogged surface openings are a major cause of hydrological failure. The rate of sedimentation depends on the amount of traffic and other sources that wash sediment into the joints, base and soil. Since the pavement is detaining runoff that contains sediment, there may be a need to eventually remove and replace the base material when the infiltration is reduced to such a degree that the pavement is no longer performing its job in storing and exfiltrating water.

Research by James (46) and practical experience have demonstrated that periodic removal of sediment in the openings will increase surface infiltration rates. Vacuum type street cleaning equipment without brooms and water spray action are the most effective at loosening and removing sediment from the openings. Regenerative air sweepers, i.e., those that blow air across the pavement surface to create a vacuum are not recommended as they tend to move the sediment rather than remove it. Likewise, brooms and water spray may move the sediment deeper into the surface openings and contribute to clogging. The frequency of vacuum cleaning will depend on the use and sources of sediment brought to the pavement openings. Vacuuming should be done at least once or twice annually and sediment/detritus deposition monitored for more frequent vacuuming. Vacuuming will have the best results when the sediment is dry which means that vacuuming during warm, dry weather will likely yield the best cleaning results. Street cleaning equipment has the potential to vacuum stones from the pavement openings, so suction adjustments may be

In-service Inspection Checklist

- ☐ Vacuum surface openings in dry weather to remove dry, encrusted sediment. These appear as small, curled “potato chips.” Vacuum settings may require adjustment to prevent uptake of aggregate in the pavement openings and joints.
- ☐ Inspect after at least one major storm per year.
- ☐ Maintained vegetation around pavement to filter runoff and minimize sediment deposition on the pavement.
- ☐ No standing water on the surface after storms.
- ☐ Repair ruts or deformations in pavement exceeding $^1/_2$ in. or 13 mm.
- ☐ Repair pavers more than $^1/_4$ in. or 6 mm above/below adjacent units.
- ☐ Replace broken units that impair the structural integrity of the surface.
- ☐ Replenish aggregate joint materials as needed.
- ☐ Check drain outfalls for free flow of water.
- ☐ Check outflow from observation well annually.

Figure 33. Owners play a key role in keeping permeable interlocking concrete pavements free from sediment, weeds, and spills. This installation filters runoff prior to entering the Chesapeake Bay in Maryland.

required. In more severe cases, vacuum equipment can withdraw soiled stones from the openings. They can then be replenished with clean aggregate. Regular surface vacuuming will maintain the infiltration performance of the pavement for years and reduce the risk of the base clogging.

All permeable interlocking concrete pavements with an open-graded base should have an observation well. The well is typically a 6 in. (150 mm) diameter perforated pipe. It has a screw cap below the surface of the pavers at least 1 in. (25 mm) that can be removed to observe the rate of exfiltration. The cap should lock and be vandal-resistant. The depth to invert should be marked on the lid. As previously noted, the observation well is located in the furthest downslope position within 3 ft (1 m) from the sides of the pavement.

Snow can be plowed from pavers as with any other pavement. Sand for tire traction will clog the surface openings and base so its use is not recommended. Deicing salts can be used on the surface. If a unit cracks from soil or base settlement, it can be removed and replaced. Likewise, the same units can be reinstated after repairs to the base, drain pipes, liners, or to underground utilities. Sealers should never be used.

Long Term Performance and Maintenance Agreements

When carefully constructed and regularly maintained, permeable interlocking concrete pavements should provide 20 to 25 years of service. Their service life is measured by the extent to which they continue storing runoff. At some point later in the life of the pavement, it may no longer store the required amount of water to control runoff. In such cases, the pavers will need to be removed, the base materials and geotextile removed and replaced. Clogged or broken drain pipes will require replacement. Once new materials are in place, the same pavers can be reinstated.

Removal and replacement of the base and pavers is an expensive operation. Other lower-cost alternatives may be possible such as cleaning or replacing selected clogged pipes (rather than the entire base and pipe system) or diverting drainage to another BMP. Ongoing maintenance and inspection are important to tracking drainage performance, sources of problems, and deciding on possible solutions.

The owner of permeable interlocking concrete pavement plays a key role in maintenance and successful long-term performance of permeable interlocking concrete pavements. The owner should have long-term ownership and oversight of the property and be aware of maintenance requirements. A growing trend to ensure oversight is a maintenance agreement. It is typically between the property owner and the local city or county, and the agreement is recorded and attached to the deed for the property.

The model agreement presented below is applicable to many BMPs. It can be edited to suit local situations and customized for the maintenance of permeable interlocking concrete pavement. A list of maintenance items should be an attachment to this agreement, as well as an inspection schedule. This list of items to be inspected can be developed from the in-service inspection check-list in this section as well as from requirements established by the local government. A growing number of local governments are creating databases in which to place BMP inspection data. This provides continual documentation of care and performance.

Model Maintenance Agreement

This Maintenance Agreement made this ____ day of ______, [year], by and between [property owner/s], hereinafter referred to as "Grantor," and the [city/county of state/province] hereinafter referred to as the "[city/county]."

WITNESSETH

WHEREAS, the [city/county] is authorized ad required to regulate and control disposition of storm and surface waters within the [city/county/watershed] as set forth by [city/county] [state/provincial] ordinances; and

WHEREAS, the Grantor is the owner of a certain tract or parcel of land more particularly described as [legal description].

ALL THOSE certain lots, pieces or parcels of land, together with buildings and improvements thereon, and the appurtenances thereunto belonging, lying, situated and being in the [city/county] of [state/province] as shown on [tax maps/subdivisions plats numbers and names], duly recorded in the Clerk's Office of the [court] of [city/county] in Deed Book or Plat Book [number] at page [number] reference to which the plat is hereby made for a more particular description thereof.

It being the said property conveyed unto the Grantor herein by deed dated _________ from _________ and recorded in the Clerk's office aforesaid in Deed Book_________ at Page_________ such property being hereinafter referred to as "the property."

WHEREAS, the Grantor desires to construct certain improvements on the property which will alter existing storm and surface water conditions on the property and adjacent lands; and

WHEREAS, in order to accommodate and regulate these anticipated changes in existing storm and surface water flow conditions, the Grantor, its heirs and assigns, desire to build and maintain at their expense a storm and surface water management facility and system [more particularly described as a permeable interlocking concrete pavement]. This is shown on plat titled _________________ and dated ____________________; and

WHEREAS, the [city/county] has reviewed and approved these plans subject to the execution of this agreement.

NOW THEREFORE, in consideration of the benefit received by the Grantor, its heirs and assigns, and as a result of the [city/county] approval of its plans, the Grantor, it heirs and assigns, with full authority to execute deeds, deeds of trust, other covenants and all rights, title and interest in the property described above hereby covenant with the [city/county] as follows:

1. Grantor, its heirs and assigns shall construct and perpetually maintain, at its sole expense, the above referenced permeable interlocking concrete pavement [storm and surface management facility and system] in strict accordance with the plan approval granted by the [city/county].
2. Grantor, its heirs and assigns shall, at its sole expense, make such changes or modifications to the permeable interlocking concrete pavement [storm drainage facility and system]. Changes or modifications may, in the [city's/county's] discretion, be determined necessary to insure that the facility and system are property maintained and continues to operate as designed and approved.
3. The [city/county], it agents, employees and contractors shall have the perpetual right of ingress and egress over the property of the Grantor, its heirs assigns, and the right to inspect [at reasonable times and in a reasonable manner,] the permeable interlocking concrete pavement [storm drainage facility and system]. Inspection is in order to insure that the system is being properly maintained and is continuing to perform in an adequate manner. [Attachment A to this agreement provides a list of items to be inspected by the [city/county]].
4. The Grantor, its heirs and assigns agree that should it fail to correct any defects in the above described facility and system within [ten (10)] days from issuance of written notice, or shall fail to maintain the facility in accordance with

the approved design standards and in accordance with the law and applicable regulations, or in the event of an emergency as determined by the [city/county] in its sole discretion, the [city/county] is authorized to enter the property to make all repairs, and to perform all maintenance, construction and reconstruction the [city/county] deems necessary. The [city/county] shall assess the Grantor, its heirs or assigns for the cost of the work, both direct and indirect, and applicable penalties. Said assessment shall be a lien against all properties described within this Maintenance Agreement and may be placed on the property tax bills of said properties and collected as ordinary taxes by the [city/county].

5. Grantor, its heirs and assigns shall indemnify, hold harmless and defend the [city/county] from and against any and all claims, demands, suit liabilities, losses, damages and payments, including attorney fees claimed or made against the [city/county] that are alleged or proven to result or arise from the Grantor, its heirs and covenant.
6. The Covenants contained herein shall run with the land and the Grantor, its heirs assigns further agree whenever the property shall be held, sold and conveyed, it shall be subject to the covenants stipulations, agreements and provisions of this Agreement, which shall apply to, bind all present and subsequent owners of the property described herein.
7. Grantor agrees to not transfer or assign responsibility.
8. The provisions of this Maintenance Agreement shall be severable and if any phase, clause, sentence or provision is declared unconstitutional, or the applicability of the Grantor, its heirs and assigns is held invalid, the remainder of this Covenant shall not be affected thereby.
9. The Maintenance Agreement shall be recorded at the Clerk's Office of the [court] of [city/county], [state/province] at the Grantor's, its heirs and assign's expense.
10. In the event that the [city/county] shall determine its sole discretion at any future time that the facility is no longer required, then the [city/county] shall at the request of the Grantor, its heirs and assigns execute a release of this Maintenance Agreement, which the Grantor, its heirs and assigns shall record, in the Clerk's Office at its expense.

IN WITNESS THEREOF, the Grantor has executed this Maintenance Agreement
On the ______ day of ______, [year].

By Officer/Authorized Agency

[State/Province] of:
[City/County] of :

To with: The foregoing instrument was acknowledged before me this______day of___________, [year], by ______________
____

References

1. U.S. Environmental Protection Agency, *Urbanization and Streams: Studies of Hydrological Impacts*, Office of Water (4503F), publication no. 841-R-97-009, Washington, DC, December 1997.
2. US Code: Title 33, Section 1329, Nonpoint source management programs.
3. Northern Virginia Planning District Commission, *Nonstructural Urban BMP Handbook*, Annandale, Virginia, December, 1999, p. 1-4
4. *Better Site Design: A Handbook for Changing Development Rules in Your Community,* Center for Watershed Protection, Ellicott City, Maryland, August 1998.
5. Tech Spec 8, *Concrete Grid Pavements*, Interlocking Concrete Pavement Institute, Washington, DC, 1999.
6. Borgwardt, S., "Performance and Fields of Application for Permeable Paving Systems," *Betonwerk + Fertigteil-Technik* (Concrete Precasting Plant and Technology), February, 1997, pp. 100 - 105.
7. Rollings, R. S. and Rollings, M. P., *SF-Rima: A Permeable Paving Stone System, SF Concrete Technologies*, Mississauga, Ontario, 1999.
8. Borgwardt, S., *Tests Performed on the Uni Eco-stone Pavements of Various Ages - Expert Opinion*, Institute for Planning Green Spaces and for Landscape Architecture, University of Hannover, Germany, July, 1994.
9. Claytor, R.A., and Schueler T. R., *Design of Stormwater Filtering Systems,* Center for Watershed Protection, Silver Spring, Maryland, December 1996.
10. Center for Watershed Protection, *Developing an Effective Best Management Practice for the Site*, Excerpts from the Center's Short Course on Practical Stormwater Management Design, Ellicott City, Maryland.
11. Debo, T. N. and Reese, A. J, *Municipal Storm Water Management*, Lewis Publishers, CBC Press, Boca Raton, Florida, 1995.
12. Borgwardt, S., "Suitable Beddings for Paving Blocks Permeable to Water," in *Betonwerk + Fertigteil-Technik* (Concrete Precasting Plant and Technology), March, 1995.
13. U.S. Weather Bureau, Rainfall intensity-duration-frequency curves for selected stations in the United States, Alaska, Hawaii and Puerto Rico. Technical Report No. 55, 1955.
14. *Canadian Climate Normals*, Atmospheric Environment Service, Environment Canada, Toronto, Ontario, Canada.
15. ASTM D 2487, Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System), *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1998.
16. ASTM D 1883, Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1998.
17. AASHTO Designation T-193, in Standard Specifications for Transportation Material and Methods of Sampling and Testing, Sixteenth Edition, Part II, Tests, American Association for State Highway and Transportation Officials, Washington, D.C., 1993.
18. ASTM D 3385, Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1998.
19. ASTM D 5093, Standard Test Method for Field Measurement of Infiltration Rate Using a Double Ring Infiltrometer with a Sealed Inner Ring, *Annual Book of ASTM Standards*, Vol. 04.08, American Society for Testing and Materials., Conshohocken, Pennsylvania, 1998.
20. *Infiltration Design Considerations and Practices to Control Stormwater Runoff*, Handout from a Short Course, Fairfax County Department of Extension and Continuing Education, Fairfax County, Virginia, 1991.
21. Asphalt Institute, *Soils Manual for the Design of Asphalt Pavement Structures*, MS-10, Fifth Edition, Lexington, Kentucky, 1993.
22. Cao, S.. L., Poduska, D. and Zollinger, D. G., *Drainage Design and Rutting Performance Guidelines for Permeable Pavement*, Texas A&M University, College Station, Texas, January 1998.
23. Rollings, R. S. and Rollings, M. P., *Design Considerations for the Uni Eco-stone Concrete Paver*, Uni-Group USA, Palm Beach Gardens, Florida, March 1993.
24. *Properties and Uses of Cement-Modified Soil*, Portland Cement Association, Skokie, Illinois, 1992.
25. Holtz, R. D. et al, *Geosynthetic Design & Construction Guidelines—Participant Notebook*, Federal Highway Administration Contract No. FHWADTFH61-93-C-00120, McLean, Virginia, 1995
26. AASHTO-AGC-ARTBA Joint Committee, *Guide Specifications and Test Procedures for Geotextiles*, Task Force 25 Report, American Association of State Highway and Transportation Officials, Washington, D.C., 1990.
27. ASTM C 936, Standard Specification for Solid Concrete Interlocking Paving Units, *Annual Book of ASTM Standards*, Vol. 04.05, American Society for Testing and Materials, Conshohocken, Pennsylvania, 1997.
28. Canadian Standards Association, A231.2-95, *Precast Concrete Pavers*, Rexdale, Ontario, 1995.

29. Canadian Standards Association, A231.1-99, *Precast Concrete Paving Slabs*, Rexdale, Ontario, 1999.

30. *Standard Specifications for Infiltration Practices*, State of Maryland, Department of the Environment, Baltimore, Maryland, 1985.

31. *Maryland Stormwater Manual*, State of Maryland, Department of the Environment, Baltimore, Maryland, 1999.

32. United States Soil Conservation Service, *Urban Hydrology for Small Watersheds*, Technical Release 55, Second Edition, Washington, D.C., 1986.

33. Ferguson, B. K., *Stormwater Infiltration*, Lewis Publishers, CBC Press, Boca Raton, Florida, 1994.

34. Ferguson, B. and Debo, T., *On-site Stormwater Management*, Second Edition, Van Nostrand Reinhold, New York, 1990.

35. Goforth, G. F., Danaus, E. V. and Rawhide, J. B., *Stormwater Hydrological Characteristics of Porous and Conventional Paving Systems.* Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1983.

36. Cedergren, H. R., *Drainage of Highway and Airfield Pavements*, Krieger Publishing Company, Malabar, Florida, 1987.

37. Diniz, Elvidio V., *Porous Pavement Phase I – Design and Operational Criteria*, EPA-600/2-80-135, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, August, 1980.

38. Thelen E. and Howe L. F., *Porous Pavement*, The Franklin Institute Press, Philadelphia, Pennsylvania, 1978.

39. Caraco, D. and Claytor, R., *Stormwater BMP Design Supplement for Cold Climates*, Center for Watershed Protection, Ellicott City, Maryland, 1997.

40. *The Asphalt Handbook*, The Asphalt Institute, MS-4, Lexington, Kentucky, 1989.

41. *ICPI Tech Spec 11, Mechanized Installation of Interlocking Concrete Pavements*, Interlocking Concrete Pavement Institute, Washington, DC, 1998.

42 Winer, R., *National Pollutant Removal Performance Database for Stormwater Treatment Practices, 2nd Edition*, Center for Watershed Protection, Ellicott City, Maryland, 2000.

43. Ferguson, B. K., *Porous Pavements*, CRC Press, Boca Raton, Florida, 2005.

44. Bean, E.Z, Hunt, W.F., Bidelspach, D.A. and Smith, J.T., *Study on the Infiltration of Permeable Pavements*, Interlocking Concrete Pavement Institute, Washington, DC, 2004.

45. Newman, A. P. et al, "Protecting Groundwater with Oil-retaining Pervious Pavements: Historical Perspectives, Limitations and Recent Developments," *Quarterly Journal of Engineering Geology and Hydrology*, Vol. 377, pages 283-291, Geological Society of London, 2004.

46. Gerrits C. and James, W., "Restoration of Infiltration Capacity of Permeable Pavers," in *Proceedings* of the Ninth International Conference on Urban Storm Drainage, Portland, Oregon, American Society of Civil Engineers, Reston, Virginia, September, 2002.

47. U.S. Environmental Protection Agency, *Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters*, EPA 840-B-92-002, Washington, DC January 1993, Chapter 4.

48. Rushton, B.T., "Low-impact Parking Lot Design Reduces Runoff and Pollutant Loads," *Journal of Water Resources Planning and Management*, May-June, 2001, pages 172-179.

49. Bean, E.Z. and Hunt, W.F., NCSU *Permeable Pavement Research Summary*, unpublished paper, Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina, 2005.

50. Scholes, L., Revitt, D.M. and Ellis, J.B., "Predicting the Pollutant Removal Potentials of Sustainable Drainage Systems," in *Proceeding*s of the Third National Conference on Sustainable Drainage, Coventry University, UK, June 20-21, 2005.

51. Clausen, J.C. and Gilbert J. K, Annual Report, Jordan Cove Urban Watershed Section 319 National Monitoring Program Project, Department of Natural Resources Management and Engineering, College of Agriculture and Natural Resources, University of Connecticut, September 1, 2003.

52. James, W. and Thompson, M.K., "Contaminants from Four New Pervious and Impervious Pavements in a Parking-lot," in *Advances in Modeling the Management of Stormwater Impacts*, Vol. 5. W. James, Editor, Computational Hydraulics Inc., Guelph, Ontario, Canada, 1997, pages 207-222.

53. Water Environment Federation, *Urban Runoff Quality Management*, WEF Manual of Practice No. 23, Water Environment Federation, Alexandria, Virginia, 1998.

54. *ICPI Tech Spec 15—A guide for the Construction of Mechanically Installed Interlocking Concrete Pavements*, Interlocking Concrete Pavement Institute, Washington, DC, 2003.

Appendix A—Glossary of Terms

AASHTO—American Association of State Highway and Transportation Officials

Aquifer—A porous water bearing geologic formation that yields water for consumption.

ASTM—American Society for Testing and Materials

Best Management Practice (BMP)—A structural or non-structural device designed to infiltrate, temporarily store, or treat stormwater runoff in order to reduce pollution and flooding.

Cation—A positively charged atom or group of atoms in soil particles that, through exchange with ions of metals in stormwater runoff, enable those metals to attach themselves to soil particles.

Choke course—A layer of aggregate placed or compacted into the surface of another layer to provide stability and a smoother surface. The particle sizes of the choke course are generally smaller than those of the surface into which it is being pressed.

Clay soils—1. (Agronomy) Soils with particles less than 0.002 mm in size. 2. A soil textural class. 3. (Engineering) A fine-grained soil with more than 50% pass the No. 200 sieve with a high plasticity index in relation to its liquid limit, according the Unified Soil Classification System.

Crushed stone—Mechanically crushed rock that produces angular particles.

CSA—Canadian Standards Association

Curve Number (CN)—A numerical representation of a given area's hydrological soil group, plant cover, impervious cover, interception and surface storage. The U.S. Soil Conservation Service (SCS) originally developed the concept. A curve number is used to convert rainfall depth into runoff volume.

Dense-graded base—Generally a crushed aggregate base with fines that, when compacted, creates a foundation for pavements and does not allow significant amounts of water into it. Particle sizes can range from 1.5 in. (40 mm) to smaller than the No. 200 (0.075 mm) sieve.

Detention pond or structure—The temporary storage of stormwater runoff in an area with objective of decreasing peak discharge rates and providing a settling basin for pollutants.

Erosion—The process of wearing away of soil by water, wind, ice, and gravity. 2. Detachment and movement of soil particles by same.

Exfiltration—The downward movement of water through an open-graded, crushed stone base into the soil beneath.

Fines—Silt and clay particles in a soil, generally those smaller than the No. 200 or 0.075 mm sieve.

Grade—1. (Noun) The slope or finished surface of an excavated area, base, or pavement usually expressed in percent. 2. (Verb) To finish the surface of same by hand or with mechanized equipment.

Gravel—1. Aggregate ranging in size from 1/4 in. (6 mm) to 3 in. (75 mm) which naturally occurs in streambeds or riverbanks that has been smoothed by the action of water. 2. A type of soil as defined by the Unified Soil Classification System having particle sizes ranging from the No. 4 sieve (4.75 mm) and larger.

Hotspot—A land use that generates highly contaminated runoff with concentrations higher than those typical to stormwater.

Hydrological Soil Group—The soils classification system developed by the U.S. Soil Conservation Service (now the Natural Resource Conservation Service) that categorizes soils into four groups, A through D, based on runoff potential. A soils have high permeability and low runoff whereas D soils have low permeability and high runoff.

Impervious cover—Surfaces that do not allow rainfall to infiltrate into the soil. Examples include pavements, roofs, sidewalks, driveways, etc.

Infiltration rate—The rate at which stormwater moves through soil measured in inches per hour or meters per second.

Karst geology—Regions of the earth underlain by carbonate rock typically with sinkholes and/or limestone caverns.

Observation well—A perforated pipe inserted vertically into an open-graded base used to monitor its infiltration rate.

One year storm—A rainfall event that occurs once a year or has a 100% chance of occurring in a given year.

One hundred year storm—A very unusual rainfall event that occurs once every 100 years or has a 1% chance of occurring in a given year.

Open-graded base—Generally a crushed stone aggregate material used as a pavement base that has no fine particles in it. The void spaces between aggregate can store water and allow it to freely drain from the base.

Outlet—The point at which water is discharged from an open-graded base through pipes into a stream, lake, river, or storm sewer.

Peak discharge rate—The maximum instantaneous flow from a detention or retention pond, open-graded base, pavement surface, storm sewer, stream or river usually related to a specific storm event.

Permeability—The rate of water movement through a soil column under saturated conditions, usually expressed as k in calculations per specific ASTM or AASHTO tests, and typically expressed in inches per hour or meters per second.

Permeable pavement – A surface with penetrations capable of passing and spreading water capable of supporting pedestrians and vehicles, e.g. permeable interlocking concrete pavement.

Pervious or permeable surfaces/cover—Surfaces that allow the infiltration of rainfall such as vegetated areas.

Porosity—Volume of voids in a base divided by the total volume of a base.

Porous pavement – A surface full of pores capable of supporting pedestrians and vehicles, e.g. porous asphalt, porous concrete (cast-in-place or precast units).

Pretreatment—BMPs that provide storage and filtering pollutants before they enter another BMP for additional filtering, settling, and/or processing of stormwater pollutants.

Retention pond—A body of water that collects runoff and stays full permanently. Runoff flowing into the pond that exceeds its capacity is released into a storm sewer, stream, lake, or river.

Sand—1. (Agronomy) A soil particle between 0.05 and 2.0 mm in size. 2. A soil textural class. 3. (Engineering) A soil larger than the No. 200 (0.075 mm) sieve and passing the No.4 (4.75 mm) sieve, according to the Unified Soil Classification System (USCS).

Sediment—Soils transported and deposited by water, wind, ice, or gravity.

Silt—1. (Agronomy) A soil consisting of particles sizes between 0.05 and 0.002 mm. 2. A soil textural class. 3. (Engineering) A soil with no more than 50% passing the No. 200 (0.075 sieve) that has a low plasticity index in relation to the liquid limit, according to the Unified Soil Classification System.

Time of concentration—The time required for water to flow from the most remote point of a watershed or catchment to an outlet.

Void Ratio—Volume of voids around the aggregrate divided by the volume of solids.

WARNING: The content of this manual is intended for use only as a guideline. It is NOT intended for use or reliance upon as an industry standard, certification or as a specification. ICPI makes no promises, representations or warranties of any kind, express or implied, as to the content of manual and disclaims any liability for damages resulting from its use. Professional assistance should be sought with respect to the design, specifications and construction of each project.

David R. Smith is the Technical Director for the Interlocking Concrete Pavement Institute or ICPI (www.icpi.org). He and 66 companies started the ICPI in 1993, and have seen this North American industry association grow to over 500 members representing producers, contractors, and suppliers. Since 1985, he has worked closely with engineers in design and construction of every kind of concrete paver project ranging from patios to streets, plus ports and airports. In addition to publishing three books, dozens of articles, guide specifications and ICPI technical bulletins on concrete pavers, Mr. Smith has written two instructional manuals for contractors. In addition, he co-authored the ICPI manuals, *Port and Industrial Pavement Design with Concrete Pavers* and *Airfield Pavement Design with Concrete Pavers*.

As a leading authority in North America on concrete segmental paving, Mr. Smith regularly speaks at national and international conferences. He is secretary-treasurer of the Small Element Paving Technologists (www.sept.org), a group of international specialists on segmental paving. He is a past chairman of the Canadian Standard Association's Technical Committee on Precast Concrete Paving. He is an active member of ASTM, having written and revised several paving product standards for that organization. He participates as a member in the American Society of Civil Engineers, American Public Works Association, Construction Specifications Institute, and the American Society of Landscape Architects (ASLA). Mr. Smith has contributed continuing education programs to the ASLA and to the American Institute of Architects.

His education includes a Bachelor of Architecture and a Masters of Urban and Regional Planning (environmental concentration) from Virginia Tech in Blacksburg. Between earning these degrees, he taught stormwater management for landscape architecture students at Virginia Tech. He also was involved in research there on concrete grid pavements and has written extensively about their design and construction. *Permeable Interlocking Concrete Pavements* represents a synthesis of experience and insights from professional engineers, stormwater regulators, and ICPI member concrete paver manufacturers and contractors.

ICPI
INTERLOCKING CONCRETE
PAVEMENT INSTITUTE ®

1444 I Street NW–Suite 700
Washington, DC 20005-6542
Tel: 202-712-9036
Fax: 202-408-02 85
E-mail: ICPI@icpi.org
Web: www.icpi.org

Permeable Interlocking Concrete Pavements

Selection • Design • Construction • Maintenance

David R. Smith

Third Edition

ICPI
INTERLOCKING CONCRETE
PAVEMENT INSTITUTE ®