IN-LB	Inch-Pound Units
SI	International System of Units

Pervious Concrete—Report

Reported by ACI Committee 522

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Pervious Concrete—Report

Reported by ACI Committee 522

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This report provides technical information on pervious concrete's application, design methods, materials, properties, mixture proportioning, construction methods, testing, and inspection.

The term "pervious concrete" typically describes a near-zero-slump, open-graded material consisting of portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water. The combination of these ingredients will produce a hardened material with connected pores, ranging in size from 0.08 to 0.32 in. (2 to 8 mm), that allow water to pass through easily. The void content can range from 15 to 35%, with typical compressive strengths of 400 to 4000 psi (2.8 to 28 MPa). The drainage rate of pervious concrete pavement will vary with aggregate size and density of the mixture but will generally fall into the range of 2 to 18 gal./min/ft² (81 to 730 L/min/m²). Pervious concrete is widely recognized as a sustainable building material, as it reduces stormwater runoff, improves stormwater quality, may recharge groundwater supplies, and can reduce the impact of the urban heat island effect.

Keywords: construction; design; drainage; green building; LEED® credit; permeability; pervious concrete pavement; stormwater; sustainability; testing.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The term "pervious concrete" typically refers to a hydraulic-cement concrete proportioned with sufficient, distributed, interconnected macroscopic voids that allow water to flow through the material under the action of gravity alone. The mixture often is composed of open-graded coarse aggregate, cementitious binder, little or no fine aggregate, admixtures, and water (Fig. 1.1a). The combination of these

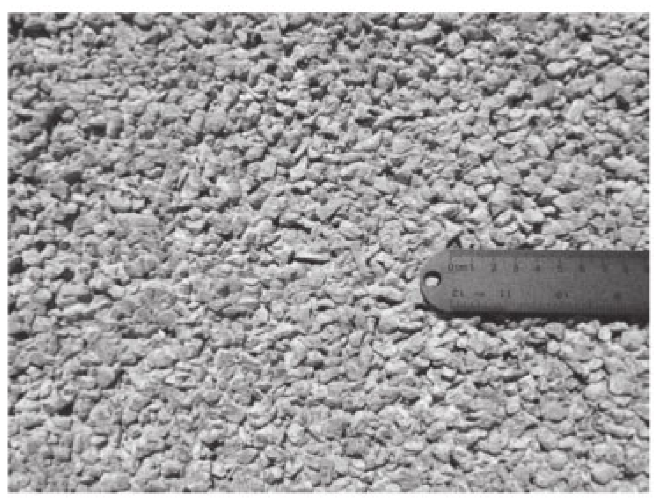

Fig 1.1a—Pervious concrete pavement (photo courtesy of M. Offenberg).

Fig 1.1b—Uniform porosity observed from a core sample (photo courtesy of J. Montgomery).

ingredients will produce a hardened material with voids (Fig. 1.1b), ranging in size from 0.08 to 0.32 in. (2 to 8 mm), that allow water to flow through easily. The void content can range from 15 to 35%. The infiltration rate of pervious concrete pavement will vary with aggregate size and density of the mixture but will generally fall into the range of 250 to 1700 in./h (0.17 to 1.20 cm/s).

1.2—Scope

The Environmental Protection Agency (EPA) recognizes that stormwater runoff is the single largest contributor to surface water impairment in the United States. Stormwater runoff also has the potential to pollute surface and groundwater supplies. Furthermore, as land is developed, stormwater runoff leaves the site in higher rates and volumes than predevelopment, leading to downstream flooding and bank erosion. Pervious concrete pavement reduces the impact of development by reducing the rate of or eliminating stormwater runoff and protecting water supplies. This report provides technical information on pervious concrete applications, design methods, materials, properties, mixture proportioning, construction methods, testing, and inspection.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_b = area of the nonpervious area to be drained, ft^2 (m^2)
A_p = area of the pervious pavement, ft^2 (m^2)
C = runoff coefficient
c = cement content, lb (kg)
D_a = diameter between coarse aggregate particles
D_c = diameter between coarse aggregate particles coated with cement paste or mortar
d_1 = thickness of the pavement, ft (m)
d_2 = thickness of the subgrade, ft (m)
f_c' = specified compressive strength of concrete, psi (MPa)
f_r = modulus of rupture of concrete, psi (MPa)
t = time, s
h_1 = initial head, in. (mm)
h_2 = final head, in. (mm)
h_c = thickness of the pervious concrete layer, ft (m)
h_{curb} = height of curb to hold ponded water, ft (m)
h_s = thickness of the subbase or reservoir layer, ft (m)
I = rainfall intensity, ft (m)
k = permeability, in./s (mm/s)
p_1 = percentage of void space in the pavement
p_2 = percentage of void space in the subgrade
R = pressure reflection coefficient
r_c = porosity of the pervious concrete layer, %
r_s = porosity for the subbase or reservoir layer, %
V = total volume of water to be drained, ft^3 (m^3)
V_p = available storage in pavement, ft^3 (m^3)
V_r = required storage volume, ft^3 (m^3)
V_s = available storage in subgrade, ft^3 (m^3)
w = water content, lb (kg)

2.2—Definitions

ACI provides a comprehensive list of acceptable definitions through an online resource, ACI Concrete Terminology. Definitions provided herein complement that resource.

exfiltration rate—the design or measure rate at which water exits the pervious concrete system.

hydraulic conductivity—the ease of which fluids pass through concrete as a function of fluid density and viscosity and degree of saturation, also known as the coefficient of permeability when referring to water under saturated conditions.

impervious area—an area covered by a material that prevents precipitation from infiltrating soils and recharging groundwater supplies.

infiltration rate—the design or measured rate at which water enters the pervious concrete surface.

percolation rate—the rate, usually expressed as inches (millimeters) per hour or inches (millimeters) per day, at which water moves through pervious concrete.

permeability—the ability of pervious concrete to allow fluids (typically water) to pass through as a function of sample volume, fluid head, and fluid viscosity.

pervious concrete—hydraulic cement concrete proportioned with sufficient, distributed, interconnected macroscopic voids that allow water to flow through the material under the action of gravity alone.

pervious pavement—a pavement comprising material with sufficient continuous voids to allow water to pass from the surface to the underlying layers.

porosity—the volume of open and connected interstitial void space in pervious concrete expressed as a percentage of the total volume.

raveling—the wearing away of the concrete surface caused by the dislodging of individual aggregate particles.

runoff—water from rain or snow that is not absorbed into the ground but instead flows over less-pervious surfaces into streams and rivers.

surface course—the top layer of a concrete pavement structure.

void content—the ratio of the volume of voids, including both entrapped and entrained air, to the total volume expressed as a percentage.

CHAPTER 3—APPLICATIONS

3.1—General

Pervious concrete is most commonly applied in parking (Fig. 3.1) and low-volume road applications for the management of stormwater volume. However, pervious concrete, much like conventional concrete, has a wide variety of applications and benefits. Some of the wide range of applications include, but are not limited to: parking lots, drainage layers, greenhouse floors, thermal insulating structural walls, acoustic barriers, tennis courts, floors for animal barns and stalls, seawalls, and artificial reefs.

Typically, unreinforced pervious concrete is used in all these applications because of the perceived high risk of reinforcing steel corrosion due to the open pore structure of the material. Noncorrosive reinforcement alternatives consisting of synthetic or natural microfibers and macrofibers are routinely included in certain areas for additional toughness and durability.

Fig. 3.1—Parking lot built with pervious concrete pavement.

3.2—Building applications: history

Pervious concrete has been used in building construction since at least the middle of the nineteenth century. Pervious concrete for building applications was first driven by lack of suitable fine aggregate and later for material conservation after World War II. Throughout this chapter, the term "pervious concrete" is used to describe the material, but in the references and historically, it may have been described as no-fines concrete or gap-graded concrete. European countries have used pervious concrete in different modes: cast-in-place load-bearing walls in single- and multi-story houses and, in some instances, in high-rise buildings, prefabricated panels, and steam-cured blocks. In 1852, pervious concrete was first used in the construction of two houses in the United Kingdom. This concrete consisted of only coarse gravel and cement. It is not mentioned in the published literature again until 1923, when a group of 50 two-story houses were built with clinker aggregate in Edinburgh, Scotland. In the late 1930s, the Scottish Special Housing Association Limited adopted the use of pervious concrete for residential construction (Francis 1965).

From 1939 to 1945, the havoc of World War II left almost all of Europe with vast housing needs, which encouraged the development of new or previously unused methods of building construction. Notably among them was pervious concrete (Malhotra 1969, 1976). Pervious concrete used less cement per unit volume of concrete as compared with conventional concrete, and the material was advantageous where labor force was scarce or expensive. By 1942, pervious concrete had been used to build over 900 houses in the United Kingdom. Elsewhere, the unprecedented demand for brick, and the subsequent inability of the brick-making industry to provide an adequate supply, led to the adoption of pervious concrete as a building material. Germany used this system because disposal of large quantities of brick rubble was a problem after the war, leading to research into the properties of pervious concrete. Similarly, in Scotland between 1945 and 1956, many homes were built with pervious concrete. This was mainly due to the presence of unlimited supplies of hard aggregates and the absence of good facing bricks. The first reported use of pervious concrete in Australia was as early as 1946. The pervious concrete system contributed substantially to the production of new houses in the United Kingdom, Germany, Holland, France, Belgium, Scotland, Spain, Hungary, Venezuela, West Africa, the Middle East, Australia, and Russia.

Before World War II, production of pervious concrete was confined to two-story homes. After 1946, however, pervious concrete was used for a much broader range of applications. It was specified as a material for load-bearing elements in buildings up to 10 stories tall (Francis 1965).

Fig. 3.2—Reinforced pervious concrete walls constructed in the early 1900s (photo courtesy of G. Seegebrecht).

Although pervious concrete has been used in Europe and Australia for the past 60 years, its early use as a building material in North America has been extremely limited. One reason for this limited use is, after World War II, North America did not experience a materials shortage as much as Europe. The earliest example of pervious concrete in the United States are the reinforced pervious concrete walls surrounding Rosehill Cemetery in Chicago, IL, constructed in the early 1900s (Fig. 3.2).

In Canada, the first reported use of pervious concrete was in 1960. Pervious concrete was used in the construction of some houses in Toronto and on a nonstructural basis in a federal building in Ottawa.

3.3—Pavement applications

3.3.1 Pervious concrete pavements' advantages over conventional concrete pavements include:

(a) Controlling stormwater pollution at the source
(b) Controlling stormwater runoff
(c) Increasing facilities for parking by eliminating the need for water-retention areas
(d) Reducing the interaction noise between tire and pavement
(e) Reducing glare on road surfaces to a great extent, particularly when wet at night
(f) Eliminating or reducing the size of storm sewers
(g) Allowing air and water to reach tree roots, even with pavement within the tree drip line (Fig. 3.3.1)
(h) Reduction in slips and falls due to the reduction in surface icing
(i) Urban heat island mitigation and permafrost protection from reduced heat storage

Pervious concrete pavements' potential disadvantages and challenges include:

(a) Limited experience in heavy vehicle traffic areas
(b) Specialized construction practices
(c) Extended curing time
(d) Sensitivity to water content and control in fresh concrete
(e) Special attention and care in design of some soil types such as expansive soils and frost-susceptible soils
(f) Lack of standardized test methods to measure compressive and flexural strength and raveling resistance
(g) Lack of a standardized design procedure for minimum infiltration requirements
(h) Special attention possibly required with high groundwater

Engineers have recommended pervious concrete in pavements as:

(a) Surface course
(b) Permeable base and edge drains
(c) Shoulders

Historically, the success of pervious pavement systems has been mixed. In many areas, pervious concrete pavement systems have been applied successfully; however, in others they have clogged in a short time or experienced excessive surface raveling. Many failures can be attributed to contractor or concrete mixture producer inexperience, higher compaction of soil than specified, and improper site design. Proper mixture designs and installation techniques have proven effective at combating clogging and raveling issues. For a pervious concrete pavement to work successfully:

(a) Permeability of soils should be verified. The permeability of the soil should, at a minimum, match that of the stormwater system design whether on a sandy subgrade or less permeable soil type. For example, in the red-clay Piedmont regions of the Carolinas and Georgia where the subgrade infiltration rate is much less than 0.5 in./h (13 mm/h), permeable pavements facilitate infiltration and filtering of runoff and recharging of the groundwater table (although they do not infiltrate the entirety of the rain water from large storms).
(b) Site layout should reduce sediment exposure from adjacent soil or vegetated areas.
(c) Construction traffic (primarily vehicular) should be directed away from the pervious pavement area during construction to prevent compaction of underlying soil layers and loss of infiltrative capacity.

Fig. 3.3.1—Pervious concrete pavement used within the drip line of trees (photo courtesy of M. Offenberg).

(d) Construction site runoff and heavy equipment should be kept away from entering the pervious pavement area. The pervious concrete pavement should not be placed into service until all disturbed land that drains to it has been stabilized by vegetation. Strict erosion and sediment controls during any construction or landscaping activity are essential to prevent the system from clogging and should be incorporated into the construction site stormwater management plan.

(e) Proper specifications should be required that clearly state the desired performance and testing requirements of the fresh and hardened concrete. Many failures have been caused by a lack of clear guidance from the designer/engineer as to what is expected of the producer and contractor.

3.3.1.1 *Parking lots*—Pervious concrete was referred to as a parking lot paving material in central Florida as early as the 1970s (Medico 1975). The concept developed as a means of handling the enormous quantities of water running off a parking lot during a storm; pervious concrete allows the water to percolate into the ground under the pavement. The Environmental Protection Agency (EPA) adopted a policy that recommends the use of pervious pavements as a part of their best management practices (BMPs) as a way for communities to mitigate the problem of stormwater runoff (U.S. EPA 2021). Pervious concrete parking lots have also been selected as an integral solution to help mitigate urban heat island effects in the Cool Communities program. The air temperature over pervious concrete parking lots is generally cooler than dense-graded asphalt. Pervious concrete parking lots also reduce snow and ice buildup and are considered a non-pollutant to the environment. The practical range of design thicknesses for pervious concrete pavements is from 6 to 8 in. (150 to 200 mm) for most parking lots.

3.3.1.2 *Sidewalks*—In many locations, pervious concrete is first used in sidewalk applications for testing and training purposes before large-scale parking lot placement. Pervious concrete sidewalks, either cast-in-place or precast, offer the same stormwater and urban heat island benefits as pervious concrete parking lots, but with the specific benefit of reduced slipping potential (Kevern et al. 2012). The practical range of design thicknesses for pervious concrete sidewalks is from 4 to 6 in. (100 to 150 mm) for sections without routine vehicular traffic.

3.3.1.3 *Roadways*—Pervious concrete for roadways is usually considered for two applications as a roadway surface or friction course. The practical range of design thicknesses for pervious concrete is from 6 to 8 in. (150 to 200 mm) for roadway pavements. Bonded overlays (Maynard 1970; Schaefer et al. 2010), however, have been as thin as 2 in. (50 mm). Numerous highways in Europe have been constructed using an overlay of latex-modified pervious concrete that allows for pavement drainage and tire-noise reduction. The latex modification results in more desirable mechanical properties (Pindado et al. 1999). A bonded 4 in. (100 mm) pervious concrete overlay constructed in 2008 at the Minnesota DOT testing facility (MNROAD) performed well with truck traffic and was one of the quietest concrete pavements in the United States, with on-board sound intensity (OBSI) testing at less than 95 dB (Schaefer et al. 2010; Kevern et al. 2011).

3.3.2 *Permeable bases and edge drains*—A pervious concrete base drains water that would normally accumulate beneath a pavement. This type of construction helps to reduce pumping of subgrade materials that could lead to the failure of the pavement. In some states, the departments of transportation have created standards for constructing drainable bases and edge drains using pervious concrete. North Dakota, California, Illinois, Oklahoma, and Wisconsin have such standard specifications (Mathis 1990). Pervious concrete in these applications is usually lower strength (1000 psi [7 MPa] or less) and is often used in conjunction with a nonwoven geotextile. A similar system can be used in slope stabilization. The runways beneath Lambert International Airport in St. Louis, MO, USA, are pervious concrete connected to a drainage system (Fig. 3.3.2).

Fig. 3.3.2—Pervious concrete base prior to conventional paving at Lambert International Airport.

Fig. 3.3.3—Pervious concrete shoulders for flood control.

3.3.3 *Shoulders*—Pervious concrete shoulders have been used in France to reduce pumping beneath concrete pavements. In the United States, pervious concrete highway shoulders have been installed in several states, including Nevada, Utah, Missouri, and New York. In New York, pervious concrete shoulders have been used to mitigate areas with flooding problems (Fig. 3.3.3).

3.4—Other applications

3.4.1 *Drains*—Water and power resource services have used pervious concrete for the construction of permeable drain tiles as well as drains beneath hydraulic structures. The drains relieve uplift pressures and allow groundwater to be drained from beneath sewer pipes.

3.4.2 *Greenhouses*—The use of pervious concrete as a thermal storage system in greenhouse floors has been investigated by researchers (Monahan 1981; Herod 1981). The floor serves as a storage area as well as a heat exchanger for the solar-heated greenhouse. Pervious concrete has also been used as paving in greenhouse floors to keep water from ponding and to eliminate the growth of weeds while providing a durable, hard surface for moving equipment.

3.4.3 *Tennis courts*—Pervious concrete has been used extensively for the construction of tennis courts in Europe. Pervious concrete slabs allow water to permeate and then drain through an aggregate base to the edges of the slab.

3.4.4 *Noise barriers and building walls*—Noises from various traffic sources or occupants of a building can be problematic. Pervious concrete noise barriers and interior walls are sometimes constructed to reduce noise. The open-graded structure tends to absorb and dissipate the sound in the material rather than reflecting it to another location.

3.4.5 *Retaining wall and abutment backfill*—Pervious concrete is an effective backfill material behind vertical retaining walls, providing resistance to erosion and reducing hydraulic pressure. The Metropolitan Atlanta Rapid Transit Authority (MARTA) has used foamed, pumpable, pervious concrete to mitigate erosion behind rail abutments (Wright 2008).

CHAPTER 4—MATERIALS

4.1—General

Pervious concrete most simply consists of ordinary portland cement, open-graded coarse aggregate, and water. Pervious concrete typically has little or no fine aggregate in the mixture. This combination forms an aggregation of coarse aggregate particles cemented together by a thin layer of hardened cement paste. This configuration produces interconnected voids (typically of sizes in the range of 0.04 to 0.2 in. [1 to 5 mm]) between the coarse aggregate, which allows water to permeate at a much higher rate than conventional concrete. Pervious concrete is considered a special type of highly porous concrete. Another distinction between these two types of porous concrete is based mainly on the void structure. Lightweight aggregate concretes contain large percentages of relatively unconnected voids. Pervious concrete, however, contains high percentages (20 to 35%) of interconnected voids, which allows for the rapid passage of water through the body of concrete.

4.2—Aggregates for use in pervious concrete

Coarse aggregate for conventional (impervious) concrete meeting gradations specified in ASTM C33/C33M may or may not possess sufficient void space to make a suitable pervious mixture. Bulk density and voids of aggregates should be determined in accordance with ASTM C29/C29M to ensure adequate voids exist to allow the specified cement content while maintaining specified void content. Aggregate gradations used in pervious concrete are open-graded coarse aggregate between the 3/8 in. (9.75 mm) and No. 4 (4.75 mm) sieves. Occasionally, larger 1/2 in. (12 mm) or 3/4 in. (19 mm) aggregates may be used in industrial applications, or finer 1/8 in. (3 mm) aggregates may be used for pedestrian applications. Rounded and crushed aggregates, either normalweight or lightweight, have been used to make pervious concrete. Research has shown the presence or addition of fine aggregate may increase compressive strengths and density but correspondingly reduce the flow rate of water through pervious concrete (Schaefer et al. 2006). Subsequent research and producer experience have shown that if there is sufficient void space in the coarse aggregate skeleton, the addition of 5% fine aggregates (sand) will decrease voids while providing other benefits such as improved resistance to freezing and thawing (Kevern et al. 2008a).

The quality of the aggregate used in pervious concrete is as important as it is in conventional concrete. Flat or elongated particles should be avoided. The narrow-graded coarse aggregate should be hard and clean, and free of coatings such as dust, clay, or other absorbed chemicals that might detrimentally affect the paste/aggregate bond or cement hydration. Aggregate sources with a service record of acceptable performance are preferable. In the absence of a source with an acceptable service record, a combination of tests could be conducted to provide a basis for assessing the suitability of a candidate aggregate for incorporation into a pervious concrete mixture (Kevern et al. 2010). Of primary importance in freezing-and-thawing conditions is to ensure the aggregate possesses soundness consistent with local acceptability. Likewise, comparative testing of similar mixtures with candidate aggregates by ASTM C1747/C1747M will provide an indication of suitability for use.

For unknown aggregate sources, results of tests conducted as per ASTM C33/C33M and ASTM D448 should be reviewed with the input of an experienced pervious mixture design consultant or materials engineer with experience in pervious concrete. Examining samples by an experienced petrographer can identify characteristics such as quality, hardness, absorption, degree of weathering, and the presence of deleterious coatings that could impair the performance of the material in service.

Aggregate moisture at time of mixing is important. The aggregate absorption should be satisfied by conditioning the stockpile as necessary to achieve saturated surface-dry (SSD) condition. Dry aggregate may result in a mixture that lacks adequate workability for placing and compaction.

Overly wet aggregates can contribute to draining of the paste, causing intermittent clogging of the intended void structure.

4.3—Cementitious materials

Portland cement conforming to ASTM C150/C150M, blended cement conforming to ASTM C595/C595M, or hydraulic cement conforming to ASTM C1157/C1157M is used as the main binder. Supplementary cementitious materials such as fly ash, slag cement, and silica fume can also be used in addition to portland cement and should meet the requirements of ASTM C618, ASTM C989/C989M, and ASTM C1240, respectively. Testing materials in trial batching is strongly recommended to verify that cement-admixture compatibility is not a problem with respect to false setting tendencies and that the setting time, rate of strength development, porosity, and permeability can be achieved to provide the characteristics needed for the anticipated placement and service conditions.

4.4—Water

Water quality for pervious concrete is governed by the same requirements as those for conventional concrete. Pervious concretes should be proportioned with a relatively low water-cementitious materials ratio (*w/cm*) (typically 0.34 to 0.41) because too much water will lead to drainage of the paste and subsequent clogging of the pore system. Too little water can result in inadequate hydration of the cement and lead to reduced strength, finishing difficulty, and raveling. The addition of water, therefore, must be monitored closely in the field. Further discussion of water quality is found in ACI 301. Recycled water from concrete operations may be usable but only if it meets provisions of ASTM C94/C94M or AASHTO M 157. In the case where hot water is used, the mixture placement should be observed to verify a lack of rapid or flash setting. Discontinue the use of hot water or halt the placement before workability of the mixture is lost.

4.5—Admixtures

Medium- or high-range water-reducers, meeting the requirements of ASTM C494/C494M, are used to improve dispersion of the cementitious material particles and improve the rheology of pervious concretes at lower *w/cm*. In those cases where water-reducing admixtures are used, they should meet the requirements of ASTM C494/C494M. Hydration stabilizing and retarding admixtures are used to stabilize and control cement hydration and are frequently preferred when dealing with low-*w/cm* mixtures, such as pervious concrete. Studies report the use of cement hydration stabilizers as an aid in extending the working time of the mixture. They are especially useful in hot weather applications (NRMCA 2009). Stabilizing/retarding admixtures can act as lubricants to help discharge concrete from a mixer and can improve handling and in-place performance characteristics. Accelerators should not be used when pervious concretes are placed in cold weather. Viscosity-modifying admixtures (VMAs) are also sometimes added to prevent drain-down. When multiple admixtures are used in a concrete mixture, it is recommended that a trial mixture placement be conducted to identify any admixture incompatibility and to verify that desired fresh and hardened properties are consistently achievable.

Air-entraining admixtures, meeting the requirements of ASTM C260/C260M, are not commonly used in pervious concretes but can be used in environments susceptible to freezing and thawing. There is no reliable method to quantify the amount of entrained air in a pervious concrete mixture (Kevern et al. 2009e). Research performed on the resistance to freezing and thawing of pervious concrete mixtures has considered the use of an air-entraining agent (Neithalath et al. 2005b; Schaefer et al. 2006; Baas 2006; Kevern 2006; Kevern et al. 2008b, 2009e). Although air entrainment cannot be easily measured, it is prudent to include an air-entraining admixture where a placement will be exposed to freezing and thawing. Incorporation of fibers for mixtures exposed to freezing and thawing has shown success in some studies to improve durability in cold climates (Kevern et al. 2008a). When used, fibers should be proportioned into the mixture from the start, not simply added to an existing mixture, as fibers can significantly change the fresh and hardened properties of the concrete.

The open void structure in pervious concrete allows moisture to rapidly evaporate from the mixture, especially in low humidity or windy conditions. The use of construction specialty chemicals is also reported to be beneficial when windy, drying ambient conditions create high evaporation rates that reduce the window of time when a mixture is most efficiently placed. The use of evaporation retarders may also be useful in this regard. It has been reported that superabsorbent polymer-based internal curing agents (ICAs) can maintain moisture in pervious concrete and provide additional water for a more complete hydration of the cement (Kevern and Farney 2012). Refer to ACI 212.3R for more information on ICAs.

CHAPTER 5—PROPERTIES

5.1—General

The various properties of pervious concrete are primarily dependent on its porosity, cementitious material content, water content, compaction level, and aggregate voids. Investigations have been based primarily on laboratory tests, with some data from actual field installations obtained. ASTM C1688/C1688M, ASTM C1701/C1701M, ASTM C1747/C1747M, and ASTM C1754/C1754M are specifically intended for use on pervious concrete. The specifier should use caution when referencing test methods for pervious concrete that are intended for conventional concrete, aggregate, masonry, asphalt, or other materials. Throughout this section, the Meininger (1988) reference is used because it is the earliest significant reference that showed pervious concrete material properties that are validated consistently across the breadth of later research.

5.2—Permeability

One of the most important features of pervious concrete is its ability to percolate water through the matrix. The

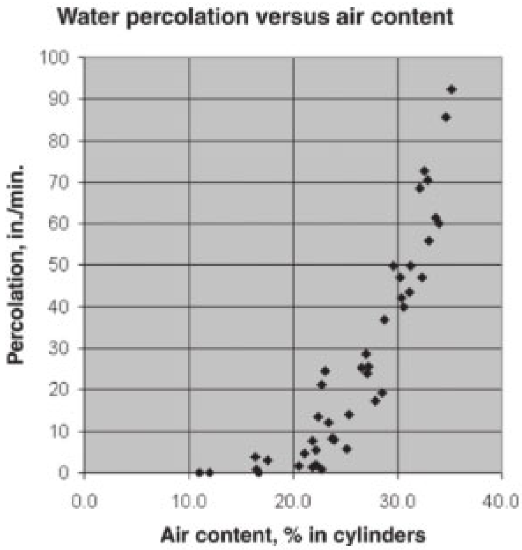

Fig. 5.2a—Relationship between percolation rate and porosity for pervious concrete (Meininger 1988). (Note: 1 psi = 0.069 MPa; 1 in. = 25.4 mm.)

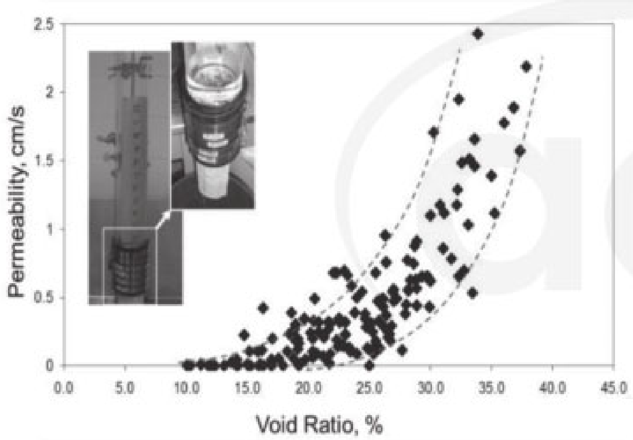

Fig. 5.2b—Influence of voids on permeability of pervious concrete (Kevern 2006). (Note: 1 cm/s = 0.394 in./s).

permeability rate of pervious concrete is directly related to the porosity and the pore sizes. Tests have shown (Meininger 1988) that a minimum porosity of approximately 15% is required to achieve significant percolation. For a porosity of 20 to 25%, the coefficient of permeability is reported be approximately 0.03 ft/s (Brite/Euram Report 1994). Figure 5.2a (Meininger 1988) shows the relationship between the air void content and permeability rate for pervious concrete mixture. Because the permeability increases as air void content increases and, consequently, compressive strength decreases, the challenge in pervious concrete mixture proportioning is achieving a balance between an acceptable permeability and an acceptable compressive strength. Because permeability is not only a function of overall porosity, but pore size as well, permeability can have a great deal of variability at a particular void content controlled by the mixture constituents. Figure 5.2b (Kevern 2006) shows the relationship between porosity and

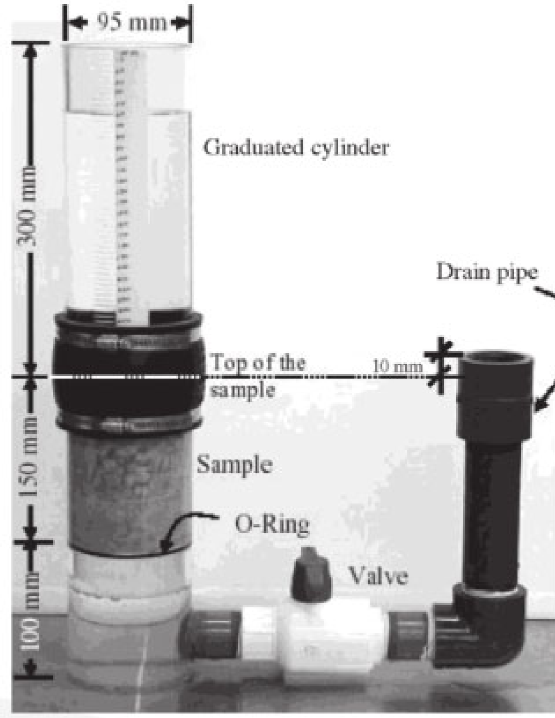

Fig. 5.2c—Apparatus for measuring permeability of pervious concrete by a simple falling-head permeameter (Neithalath et al. 2003). (Note: 1 mm = 0.0394 in.)

permeability for numerous mixtures containing different mixture proportions and mixture components.

The permeability of pervious concrete can be measured by a simple falling-head permeameter as shown in Fig. 5.2c (Neithalath et al. 2003). In this approach, the sample is enclosed in a latex membrane to avoid water flowing along the sides of the specimen. Water is added to the graduated cylinder to fill the specimen cell and the draining pipe. The specimen is preconditioned by allowing water to drain out through the pipe until the level in the graduated cylinder is the same as the top of the drainpipe. This minimizes any air pockets in the specimen and ensures that the specimen is completely saturated. With the valve closed, the graduated cylinder is filled with water. The valve is then opened, and the time in seconds t required for water to fall from an initial head h_1 to a final head h_2 is measured. An initial head h_1 of 10 in. (250 mm) and a final head h_2 of 1 in. (25 mm) have shown to work well in practice. The permeability k (in./s [mm/s]) can be expressed as

$$k = A/t$$

where A is a constant equal to 7.7 in. (192 mm).

A simple triaxial flexible-wall constant-head permeameter has been used to determine the permeability of pervious portland-cement concrete (PCC) in the range of 1 to 14,000 in./h (0.001 to 10 cm/s) (Crouch et al. 2006). Constant-head permeability appears to be a function of paste drain-down, effective air void content, and void size. The results of the falling-head and constant-head methods agree reasonably for laboratory samples.

Apart from the porosity and pore size, a crucial factor that influences the permeability of pervious concrete is the pore tortuosity or the degree of connectivity of the pore network. There is no straightforward methodology to measure the pore connectivity of pervious concrete. Neithalath et al. (2006) investigated the use of electrical impedance-based methods to determine the pore connectivity factor of pervious concretes to link it to the hydraulic characteristics of the material. Additionally, X-ray-computed tomography has been used to accurately determine of pore connectivity in pervious concretes (Kevern 2006).

The environmental benefits of pervious concrete have been well documented. Deo et al. (2008) investigated the efficiency of pervious concrete in retaining vehicular oil spills in its material structure using carefully designed experiments and modeling. Pervious concrete mixtures with porosities ranging from 13 to 25% were proportioned using two different size aggregates. The oil retention and recovery were experimentally determined on 2 in. (50 mm) slices of pervious concrete specimens using a partition gravimetric method. It was observed that a porosity of 20% is ideal for optimal oil retention in the pore structure of the material. An idealized pore-aperture model was used to develop a modeling framework for the oil retention in pervious concrete. The material parameters as well as the input features that are most likely to influence the retention and recovery of oil were identified. A genetic programming-based model was used to predict the oil retention in pervious concrete specimens. This modeling methodology provides good estimates of oil retention. The performance of the genetic programming-based model was judged in terms of its error statistics. Results obtained from this model were more reliable than those obtained using a linear regression method with the same input parameters. The study is expected to lead to further tests on optimization of pore structure of pervious concrete for applications including oil retention and water transport.

5.3—Compressive strength

The compressive strength of pervious concrete is strongly affected by the mixture proportion and compaction effort during placement. Meininger (1988) investigated the relationship between pervious concrete compressive strength and void content. Results are shown in Fig. 5.3a. In this study, the series of laboratory tests was performed on two sizes of coarse aggregate. The compaction effort and aggregate gradation were varied for each size of aggregate. Kevern (2006) investigated the same relationship of pervious concrete compressive strength and void content but used more varied mixture proportions, including various aggregate types, aggregate sizes, aggregate gradations, paste contents, paste compositions, and *w/cm* (Fig. 5.3b). Fundamentally, both studies show that there is a strong relationship between void content and compressive strength; however, mixtures can be modified to improve compressive strength for a particular void content. Mulligan (2005) also indicates that there is a relationship between pervious concrete compressive strength and unit weight (Fig. 5.3c). Although his study only used one size of coarse aggregate, the compaction effort and the aggregate-cement ratio were varied. The data of Meininger (1988) indicate that relatively high compressive strengths of pervious concrete mixtures

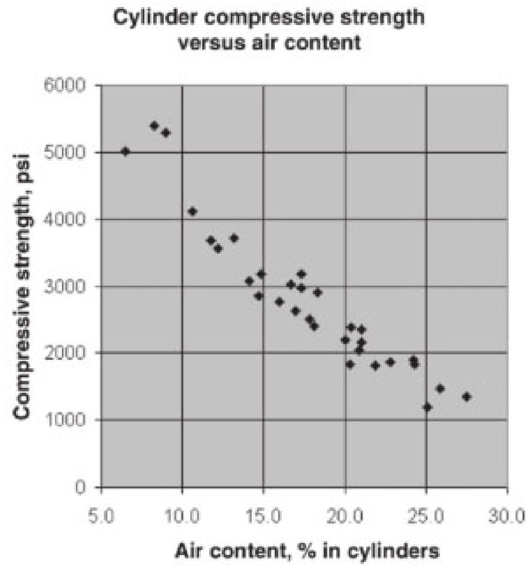

Fig. 5.3a—Relationship between compressive strength and porosity for pervious concrete (Meininger 1988). (Note: 1 psi = 0.0069 MPa.)

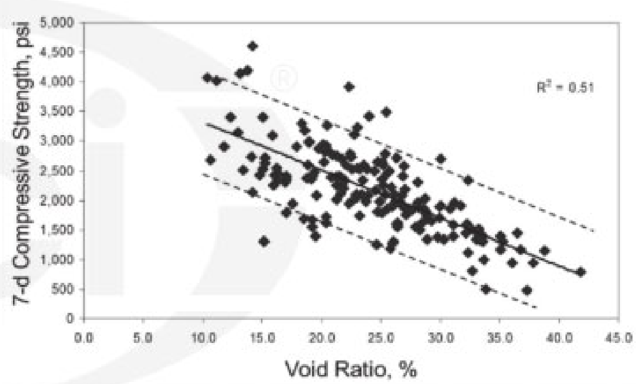

Fig. 5.3b—Relationship between compressive strength and porosity for pervious concrete (Kevern 2006). (Note: 1 psi = 0.0069 MPa.)

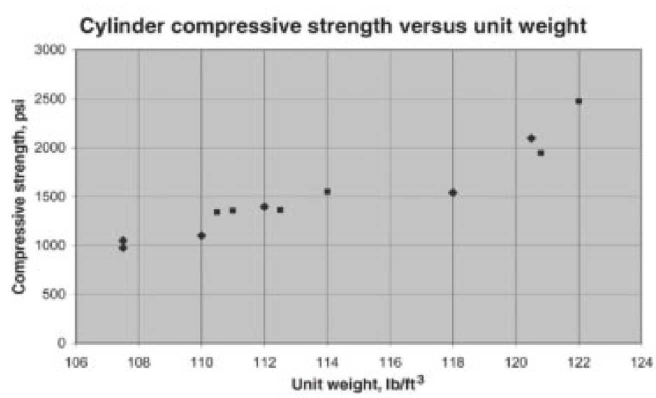

Fig. 5.3c—Relationship between unit weight and compressive strength for pervious concrete (Mulligan 2005). (Note: 1 psi = 0.0069 MPa; 1 lb/ft³ = 16.02 kg/m³.)

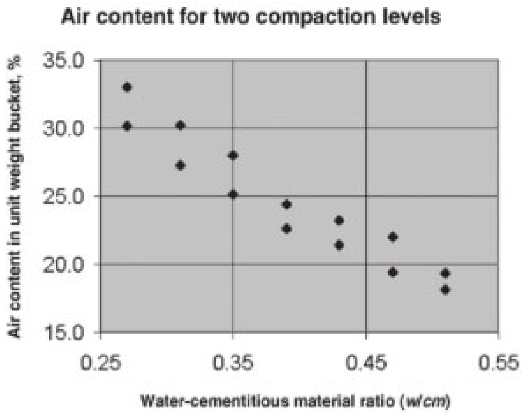

Fig. 5.3d—Relationship between air content (porosity) and w/cm *for pervious concrete at two compaction levels (Meininger 1988).*

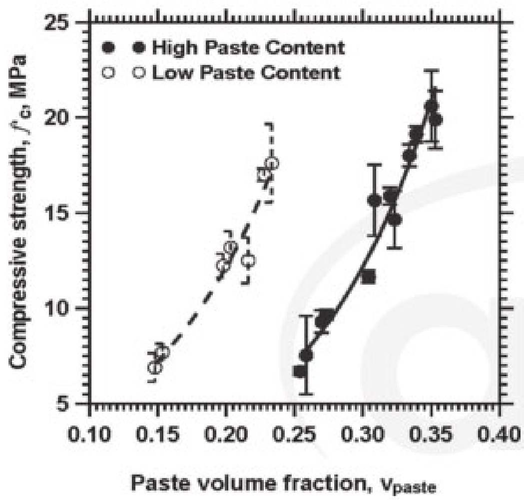

Fig. 5.3e—Relationship between paste volume and compressive strength (Deo and Neithalath 2011). (Note: 1 MPa = 145 psi.)

are possible, but that high strength is achieved only with the reduction of void content (Fig. 5.3a). However, the reduction in air voids results in a loss in percolating efficiency of pervious concrete. Suleiman et al. (2006) reported that an 11% decrease in compressive strength was observed when the vibration amplitude of the compactor is reduced to 0.0034 in. (0.086 mm) from 0.005 in. (0.127 mm). Crouch et al. (2006) reported that an increase in fineness modulus of the aggregates reduces the compressive strength. Mahboub et al. (2008) cautions that field cored strengths can be significantly different than cast test cylinders.

Although the *w/cm* of a pervious concrete mixture is important for the development of compressive strength and void structure, the relationship between the *w/cm* and compressive strength of conventional concrete does not apply to pervious concrete. A high *w/cm* can result in the paste flowing from the aggregate, filling the void structure. A low *w/cm* can result in reduced adhesion between aggregate particles, resulting in low density and raveling. The relationship between the *w/cm* and void content of a pervious concrete mixture (with cement and aggregate content held constant) at two different compaction levels is given in Fig. 5.3d (Meininger 1988). Experience has shown that a *w/cm* of 0.34 to 0.41 provides good aggregate coating and paste stability. When fine aggregates are used in pervious concrete proportioning, the grain size of the fine aggregate in relation to the coarse aggregate is believed to influence the porosity and, consequently, the compressive strength of the material (Onstenk et al. 1993).

The total cementitious material content and resultant paste content of a pervious concrete mixture are important for the development of compressive strength and void structure. An excessive paste content may result in a filled void structure and, consequently, reduced porosity. An insufficient cementitious material content can result in reduced paste coating of the aggregate and reduced compressive strength. The optimum cementitious material content is strongly dependent on aggregate size and gradation. For the aggregate selected, binder drainage tests are recommended to ascertain the optimum cementitious material content (Nelson and Phillips 1994). In some cases, reduction of the total cementitious material content of the mixture allows the use of increased water content with a resulting increase in workability, without affecting the overall paste content.

Another factor that can have a significant impact on the strength of pervious concrete is the thickness of the paste layer surrounding the aggregate. Paste thickness is related to the aggregate size, cementitious material content, and the *w/cm*. The paste thickness and aggregate size influence the pore features of pervious concrete and influence strength separately from just porosity. The mean free spacing between the pores was also shown to influence ultimate strengths of pervious concretes (Deo and Neithalath 2010). In a companion study, Deo and Neithalath (2011) found a statistically significant strength-to-porosity relationship irrespective of the total paste contents in the mixtures. Distinct trends relating the paste content to the compressive strength were observed for both the low and high paste contents, as shown in Fig. 5.3e. The effects of relative volumes of aggregates and the compaction effort would need to be considered when paste contents are related to compressive strength of pervious concretes.

5.4—Flexural strength

The relationship between pervious concrete flexural strength and void content based on beam specimens is shown in Fig. 5.4a (Meininger 1988). Although these results are based on a limited number of specimens, comparing the data in Fig. 5.3a and 5.4a indicates that a relationship between the compressive and flexural strengths of pervious concrete exists. This relationship, like compressive strength, depends on several variables. The relationship between compressive and flexural strengths of pervious concrete for one laboratory test series is shown in Fig. 5.4b (Meininger 1988). The addition of a small amount of sand (approximately 5% by volume) increases the flexural strength of pervious concrete (Neithalath 2004). An increase in flexural strength of pervious concrete has been reported when a polymer additive is used (Onstenk et al. 1993). Flexural strength

of approximately 535 psi (3 MPa) has been observed for a pervious concrete proportioned using 1/4 to 3/8 in. (6 to 10 mm) aggregates and having 25% porosity (Nissoux et al. 1993; Brite/Euram Report 1994). The ability to achieve high flexural strengths for pervious concrete was demonstrated by a wearing course overlay, which achieved 900 psi (6.2 MPa) (Schaefer et al. 2011).

Crouch et al. (2006) investigated the relationship between flexural strength f_r and compressive strength f_c' for pervious pavement. They determined that the relationship most closely matches the equation established by Shah and Ahmad (1985) for precast concrete.

$$f_r = 2.3 f_c'^{2/3} \quad \text{(in.-lb)}$$
$$f_r = 0.083 f_c'^{2/3} \quad \text{(SI)} \qquad (5.4)$$

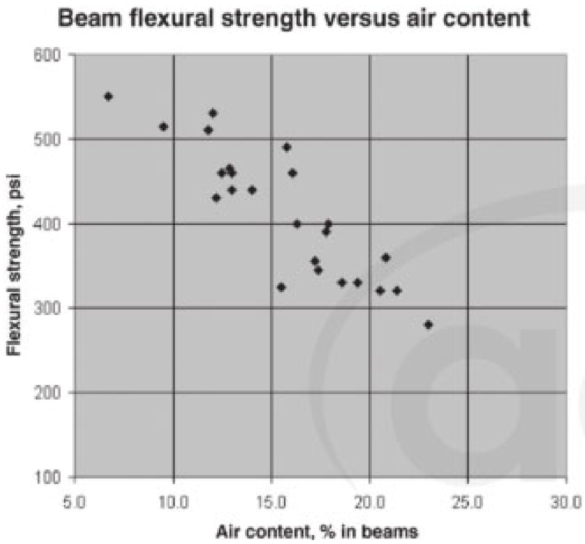

Fig. 5.4a—Relationship between flexural strength and porosity for pervious concrete (Meininger 1988). (Note: 1 psi = 0.0069 MPa.)

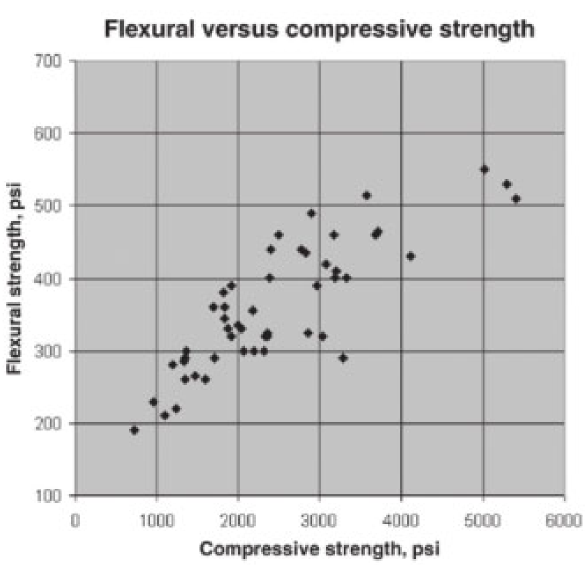

Fig. 5.4b—Relationship between flexural strength and compressive strength for pervious concrete (Meininger 1988). (Note: 1 psi = 0.0069 MPa.)

5.5—Durability under freezing-and-thawing conditions

ACI Concrete Terminology (CT-21) defines durability as "the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service." When possible, it is important to design the system so that the pervious concrete is not saturated when it freezes. Many factors influence this, including strength, porosity, the ratio of impervious to pervious areas, and frequency of maintenance (cleaning). Apart from the porosity and pore size, a crucial factor that influences the flow of water through pervious concrete is the pore tortuosity or the degree of connectivity of the pore network. The mixture factors that have the greatest influence on pervious concrete freezing-and-thawing resistance are air entrainment, including fine aggregate; *w/cm*; and aggregate durability (Kevern et al. 2008c, 2010).

5.5.1 *Air entrainment*—While the pervious concrete system should not be designed to store water in the concrete pore space in climates that are subject to freezing-and-thawing conditions, situations may exist when the pavement is wet and the paste is saturated without having the voids filled. Clogged specimens also have an increased degree of saturation compared to unclogged samples in wet-freeze environments, which increases freezing-and-thawing damage (Guthrie et al. 2010). Consequently, mixtures subject to freezing should be designed for durability to freezing-and-thawing conditions, although testing of fully saturated pervious concretes may be overly severe and may indicate a worst-case scenario. However, the standard laboratory test for evaluating the durability of pervious concretes when subjected to cycles of freezing and thawing is ASTM C666/C666M, Procedure A, where samples are frozen and thawed rapidly in the saturated condition. A slower freezing condition—one cycle per day as compared with five or six per day as stated in ASTM C666/C666M, Procedure A—may allow the water to drain from the pervious concrete, improving results as compared to Procedure B, where the samples are thawed in water (Neithalath et al. 2005b).

Laboratory tests indicate that entraining air in the cement paste improves resistance to cycles of freezing and thawing for pervious concrete (Kevern et al. 2008b, 2009e). In the laboratory under ASTM C666/C666M test conditions, non-air-entrained pervious concrete samples failed (relative dynamic modulus drops to less than 60%) in 100 cycles or less of freezing and thawing in the chamber (ASTM C666/C666M requires a standard 300 cycles for the test). Also, pervious concrete specimens subjected to slow freezing and thawing (one cycle per day) suffered less damage than those subjected to the ASTM C666/C666M Procedure A test, where samples were subjected to five to seven cycles a day (Neithalath et al. 2005b). Another study shows that partially saturated pervious concrete subjected to freezing and thawing in air demonstrated substantially higher durability than those subjected to freezing and thawing while submerged under water (Yang et al. 2006). This suggests the need for routine surface cleaning of pervious concrete such that clogging and surface ponding are prevented.

5.5.2 *Inclusion of fine aggregate or fibers*—The addition of small dosages of fine aggregate or synthetic fiber has been reported to increase the freezing-and-thawing resistance (Wang et al. 2006; Kevern 2006; Kevern et al. 2008a, 2015). The fine aggregate increases the cementitious material paste viscosity, allowing a thicker film of paste to surround each aggregate particle. When those aggregate particles come in contact during placement, the contact area between the particles is increased from the thicker paste film, resulting in greater load transfer and higher strength. The angle of incidence between the particles is also reduced, which helps protect against freezing-and-thawing stresses. Fibers help hold the aggregate particles together, retaining more mass and increasing freezing-and-thawing performance.

Macro-synthetic fibers in higher dosages contribute more to pervious durability than micro-synthetic fibers in low dosages. Macro-fibers have shown considerable enhancements to the Mass Durability Factor and Relative Durability Factor in freezing-and-thawing testing of pervious concrete (Kevern et al. 2015). Per ASTM C666/C666M-A research, macrofiber (5.0 lb/yd^3 [3 kg/m^3], 2.25 in. [57 mm] long) specimens easily survived 300 freezing-and-thawing cycles essentially intact, as compared to plain control specimens that failed completely at 187 cycles (Kevern et al. 2015).

5.5.3 *Water-cementitious materials ratio*—One additional study (Kevern et al. 2008c) investigated the performance of a single mixture produced at *w/cm* from 0.25 to 0.32 with admixture dosages held constant to simulate unanticipated water changes that could occur at a construction site. Results indicated that at very low *w/cm* (0.25, 0.26), the paste was dry, voids were high (28 and 24%), and, consequently, freezing-and-thawing resistance was poor (74 and 95 cycles to failure, respectively). As water was added, the mixture became more workable and the voids were reduced to approximately 16%. The increased workability and water content improved freezing-and-thawing resistance to 300 cycles for *w/cm* of 0.31 and 0.32. For this set of mixture proportions, paste drain-down occurred above a *w/cm* of 0.32. As first mentioned in Section 5.2, *w/cm* trends are different for pervious concrete, and this study showed that a properly wetted paste is more important than a low *w/cm* for resistance to freezing and thawing.

5.5.4 *Aggregate durability*—A study performed for the Portland Cement Association (PCA) evaluated the resistance to freezing and thawing of pervious concrete that was produced using coarse aggregate types from different locations in the United States and Canada. Mixtures were produced using the same proportions to evaluate effects of the aggregate. Results indicate that statistically significant factors include specific gravity and absorption. Aggregates with higher specific gravity (an average of 2.64) and lower absorption (an average of 0.82%) had good freezing-and-thawing resistance whereas samples with unacceptable freezing-and-thawing resistance had lower specific gravity (2.57) and higher absorption (2.27%). For a single mixture design, porosity, unit weight, compressive strength, and tensile strength did not correlate to freezing-and-thawing performance for any of the different aggregates (Kevern et al. 2010).

5.5.5 *Application of deicing chemicals*—In locations where freezing-and-thawing resistance is a concern, resistance to deicing salts is also a significant deterioration mechanism. Research performed by Cutler et al. (2010) showed that for pervious concrete produced with 50% replacement for cement with Class C fly ash and blast-furnace slag, samples containing a latex-based admixture had much poorer resistance to deicing salts than the mixture without. Calcium chloride produced the greatest deterioration followed by sodium chloride, then calcium-magnesium acetate, and little deterioration was caused by distilled water. Recommendations from the study include avoiding latex-based admixtures and calcium chloride for deicing applications (Cutler et al. 2010). Other studies have demonstrated that magnesium chloride deicer damages concrete materials. This is due to chemical attack on the cement that reduces its binding capacity through the formation of brucite. This reaction occurs at above-freezing temperatures. (Sutter et al. 2008; Sumsion and Guthrie 2013).

Furthermore, field experience and experimental results indicate severe deterioration when deicing chemicals are applied at early ages after installation, and with prolonged heavy use of deicing products. Therefore, deicing products should be avoided as much as possible, particularly in the first year after placement.

5.6—Surface abrasion and raveling resistance

Raveling is a primary deterioration mechanism of pervious concrete, not only affecting the surface appearance and smoothness, but also reducing permeability. ASTM C1747/C1747M measures the mass loss of samples abraded in the Los Angeles (LA) abrasion device for 500 revolutions. ASTM C944/C944M determines surface abrasion through mass loss and depth of wear from weighted dressing wheels abrading the concrete surface at 200 rpm for 2 minutes. ASTM C1747/C1747M is more applicable for evaluating different mixtures (Offenberg 2011), whereas ASTM C944/C944M can determine improvements from curing compounds or surface treatments.

Surface abrasion testing has allowed verification of the most appropriate curing and repair methods. Curing under plastic has been shown more effective than surface-applied curing compounds alone (Kevern et al. 2009b). However, as with other admixtures, samples internally cured using a super-absorbent polymer had better abrasion resistance than a conventional pervious concrete mixture, even under hot and dry conditions (100°F [32°C] and 32% relative humidity). One additional activity investigated techniques to reduce raveling when samples were cured under the same hot and dry conditions. Surface-applied sodium silicate densifier, traditionally used to harden polished concrete floors, was able to reduce raveling by 50% without affecting porosity or permeability (Kevern and Sparks 2013). Both micro-synthetic and macrosynthetic fibers have also shown the ability to significantly reduce raveling when tested using the ASTM C944/C944M method (Kevern et al. 2009b, 2015).

5.7—Fracture toughness

Synthetic fibers can be employed to increase toughness. Toughness can be quantified in one of several test methods, such as ASTM C1399/C1399M. This test produces a post-crack strength value in psi that relates to the flexural strength of the concrete matrix. Product testing of synthetic fibers in beam specimens of pervious concrete in accordance with ASTM C1399/C1399M demonstrated that fibers 1.5 to 2.0 in. (40 to 50 mm) in length were the most effective in imparting toughness to the concrete (SI Concrete Systems 2002).

The fracture toughness of pervious concretes, in addition to the use of fiber reinforcement, also depends on the pore structure features. The material fracture parameters—the critical stress intensity factor (K_{IC}) and the critical crack tip opening displacement ($CTOD_c$)—were determined using three-point bend tests on notched beams in a study (Rehder et al. 2014). Two different porosities (ϕ_d) designed using a particle-packing-based methodology with two different aggregate sizes (and, hence, pore sizes) were used to demonstrate the influence of the pore structure features on fracture toughness (Rehder et al. 2014). Contrary to conventional concretes, the larger pore size in pervious concretes somewhat inhibits the influence of fibers in enhancing the fracture toughness. This relationship was computationally determined from three-dimensional reconstruction (Sumanasooriya et al. 2010).

5.8—Acoustic absorption

Due to the presence of a large volume of interconnected pores of considerable sizes in the material, pervious concrete is highly effective in acoustic absorption. The material can be employed to reduce noise generated by tire-pavement interaction on concrete pavements. Noise reduction occurs from a combination of reduced noise generation and increased sound absorption. Pervious pavements alter the generation of noise by minimizing the air pumping between tire and road surface. In addition, pores absorb sound through internal friction between the moving air molecules and the pore walls.

To evaluate the sound absorption characteristics of pervious concrete, an impedance tube can be used as shown in Fig. 5.8 (Neithalath 2004; Marolf et al. 2004). Cylindrical specimens with a diameter of 3.75 in. (95 mm) can be accommodated in the impedance tube. The sample is placed inside a thin cylindrical polytetrafluoroethene (PTFE) sleeve, into which it fits snugly. The sample assembly is placed against a rigid backing at one end of the impedance tube, which is equipped with a sound source. A plane acoustic wave is generated by the sound source and propagates along the tube axis. Microphones placed along the tube's length are used to detect the sound wave pressure transmitted to the sample and portion of the wave that is reflected (ASTM E1050). The pressure reflection coefficient R is the ratio of the pressure of reflected wave to that of incoming wave, at a particular frequency.

The absorption coefficient is a measure of a material's ability to absorb sound. A material with an absorption coefficient of 1.0 indicates a purely absorbing material, whereas a material with an absorption coefficient of 0 indicates the material is purely reflective. Normal concrete, for example, typically has an absorption coefficient of 0.03 to 0.05 (Neithalath 2004). Pervious concrete typically has an absorption range from 0.1 (for poorly performing mixtures) to nearly 1 (for mixtures with optimal pore volume and sizes). Because the absorption coefficient depends on the frequency of impinging sound waves, it is important to determine the minimum pervious concrete thickness that will minimize sounds of the desired frequency. Values between 800 and 1200 Hz are the most objectionable to the human ear.

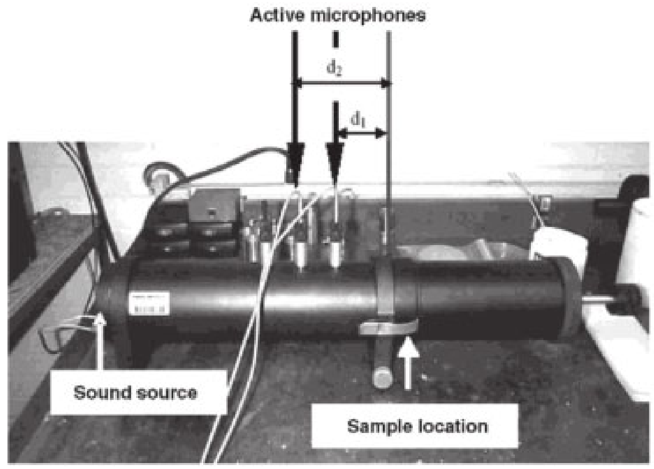

Fig. 5.8—Impedance tube for measuring the sound absorption characteristics of pervious concrete (Neithalath 2004; Marolf et al. 2004).

In 2008, a pervious concrete overlay was constructed as part of the Federal Highway Administration (FHWA) surface characteristics program to evaluate the potential for pervious concrete to mitigate noise in urban areas. AASHTO T 360 averages leading and trailing edge microphones near a standard tire on a standard vehicle traveling at 60 mph (97 km/h). Using this testing method, pavements with results less than 100 dB are considered quiet pavements (Schaefer et al. 2011). On-board sound intensity (OBSI) results from the pervious concrete overlay show values between 90 and 96 dB (Schaefer et al. 2010). Those results show that pervious concrete pavements can be 50 to 100% quieter than current quiet conventional pavements. Complete details are provided in Schaefer et al. (2010).

5.9—Slip and fall prevention

Although intuitively and anecdotally observed to be a more slip-resistant walking surface, prior to a recent study, no empirical evidence existed to characterize pervious concrete as a walking surface with superior slipping properties in comparison to traditional concrete. A unique testing program was developed at the Human Motion Laboratory at the University of Missouri-Kansas City using biomechanical evaluation to investigate pervious concrete's impact on slipping characteristics during gait. The pervious concrete samples tested had 30% voids, high permeability with infiltration rates greater than 1300 in./h (1.0 cm/s). Pervious samples were found to have 45% of the surface

area compared to traditional concrete within a zone for potential shoe contact. Shoe-to-pavement contact pressure for pervious concrete was found to be more than twice that for traditional concrete pavement. The dry pervious concrete pavement also had coefficient of friction two to three times greater than the traditional concrete. When icy, the greatest difference in coefficient of friction between the two surface types occurred between 25 and 30°F (–4 and –1°C), with less slipping occurring on the pervious concrete. The additional contact pressure, coefficient of friction, and reduced potential for ponding water and surface freezing indicated pervious concrete may be a more slip-resistant walking surface in winter conditions (Kevern et al. 2012).

5.10—Urban heat island mitigation

Pavements contribute to the urban heat island (UHI) effect due to their bulk mass and heat absorption capacities. Granular ground surfaces composed of soils or sands do not contribute to the UHI effect in a similar manner. Their porous nature may lessen the effect both with an increased insulating capacity and with an enhanced mechanism for evaporative cooling from absorbed water. Pervious concrete has a network of interconnected voids that allow water exfiltration to the subbase below. Limited studies on pervious concrete indicate that the pervious concrete surface can have elevated temperatures as compared with similar traditional impervious pavements, but that temperatures are lower under the pavements.

Studies have been performed in Iowa, South Carolina, and Washington where both a pervious concrete and a traditional concrete paving system have been installed and temperatures recorded within the systems for extended time periods (Kevern et al. 2009a,c; Haselbach and Gaither 2008). The analyses covered days with negligible antecedent precipitation and high air temperatures—extreme conditions for UHI impacts. Results showed that less energy is stored during heating in pervious concrete systems than the traditional concrete systems. This was using similar cementitious material mixtures for both pavements (similar cement colors) and where, based on previous research, the pervious concrete surface would have a lower solar reflectance and, hence, a higher surface temperature under similar solar radiation conditions.

A strategy for mitigating the UHI effect may be to employ lower energy storage pavement systems. Using pervious concrete systems with their layers of materials with higher porosity than traditional pavement systems may be an effective tool in reducing the UHI effect. Considerations of material characteristics below grade such as porosity are important in determining a permeable pavement's capacity for heat island mitigation. Solar reflectance should not be used independent of these other variables, and pervious concrete pavement is considered a cool pavement solution in the International Green Construction Code (IgCC) regardless of color (Kevern et al. 2009a; ICC IgCC 2021).

5.11—Pollutant removal capacity

Pervious concrete pavement systems have been shown to have high capacity for stormwater pollutant removal. Some of the removal process is by physical filtration of the particulates in the stormwater, with the pollutants either remaining on the surface or within the system. Examples of pollutants with high removal efficiencies are solids, hydrocarbons, and metals. In addition, there are opportunities within the systems for chemical removal by sorption or ion exchange or, in the case of oils or other hydrocarbons, microbial degradation. This may occur in pervious concrete but has been observed within the underlying system, including the aggregate subbase and soil (Pratt et al. 1999). The pervious concrete layer itself has been shown to have substantial capacity for long-term zinc and copper removal due to the chemistry of the concrete (Ahiablame et al. 2012; Haselbach et al. 2014a; Rushton 2001).

CHAPTER 6—PERVIOUS CONCRETE MIXTURE PROPORTIONING

6.1—General discussion of proportioning

For pervious concrete, the cement factor (coarse aggregate to cementitious materials ratio) and *w/cm* are the major variables affecting the mechanical characteristics. A wide range of cement factors has been found to be acceptable, depending on the specific application and desired performance. Chemical admixtures, in addition to affecting the *w/cm,* are used to influence paste content, workability and setting times, enhance various mechanical characteristics of pervious concrete, and improve long-term durability. Currently, there is not a standardized test for strength and strength testing is not appropriate as an acceptance criteria. Durability in terms of resistance to raveling is determined using ASTM C1747/C1747M.

The process of developing mixture proportions for pervious concrete is often repeated through successive iterations. For example, a series of trial batches may be developed in the laboratory and then tested in the field to ensure expected behavior and performance. In general, pervious concrete mixtures are proportioned to achieve a balance among voids, paste content, workability, and durability.

6.2—Proportioning criteria

The optimum water content produces a fully wetted cementitious paste with sufficient viscosity to cover the coarse aggregate particles without the paste draining from coarse aggregate and clogging the pores of the pervious concrete. A fully wetted cementitious paste is often described as having a wet metallic appearance or sheen. For a given set of mixture proportions containing a particular aggregate size, type, and admixture dosages, there is a smaller range of acceptable *w/cm* than typical for conventional concrete. The cementitious paste creates sufficient bond between the aggregate particles while providing sufficient void volume for the infiltration of water. The *w/cm* is an important consideration for obtaining the desired durability and void structure in pervious concrete. A high *w/cm* reduces the adhesion of the paste to the aggregate and causes the paste to flow and fill the voids even when lightly compacted. A low *w/cm* will prevent thorough mixing and tend to cause balling

in the mixer, prevent an even distribution of cement paste, reduce the adhesion of the paste to the aggregate, and therefore reduce the ultimate strength and durability of the concrete. Low *w/cm* is often a cause of early-age raveling (1 to 7 days). For pervious concrete, the *w/cm* to obtain the desired workability usually falls within 0.30 to 0.40. The conventional *w/cm*-versus-compressive strength relationship for normal concrete does not directly apply to pervious concrete. Careful control of aggregate moisture and *w/cm* is important to produce consistent pervious concrete.

Determining the desired void content for pervious concrete is a balancing act between infiltration rate and compressive strength, with a higher infiltration rate resulting in lower strength and durability. The intent is to find a mixture that provides at least an initial infiltration rate that is neither too low nor too high. Low surface infiltration rates are susceptible to rapid clogging from fine materials carried in the stormwater. High infiltration rates might be susceptible to deep clogging from larger sediments or solids and are often susceptible to high surface raveling. Generally, pavements with infiltration rates between 250 and 1000 in./h (6.35 to 25.4 m/h) provide adequate strength and durability while providing good resistance to clogging (Kevern 2011; Kevern et al. 2015). The initial infiltration rates in these ranges are always much higher than are needed for typical stormwater balances and, therefore, increased rates are not usually beneficial. Instead, clogging issues and cleaning options should be considered.

Compressive strength and durability of pervious concrete are also a function of the aggregate strength, paste bonding characteristics, and strength of the cement paste itself. Some caution should be used when applying these quantitative numbers to practical design, as standardized test methods do not yet exist for these properties of pervious concrete; prior discussion should be taken as purely a qualitative characterization.

6.3—Proportioning process

In the same fashion as conventional concrete, a wide variety of different techniques exist to proportion pervious concrete. The following is a simple technique to develop a starting mixture for further iteration. Please review Chapters 4 and 5 for desired materials and material characteristics.

Step 1—Select coarse aggregate: Select a coarse aggregate with at least 38% voids as determined by ASTM C29/C29M for dry rodded unit weight (DRUW).

Step 2—Determine required coarse aggregate: Multiply the DRUW by 0.95 if no fine aggregate is present or 0.90 if fine aggregate is present to accommodate for the volume of film paste separating the coarse aggregate pieces, as shown in Fig. 6.3a. The diameter between the coarse aggregate particles (D_a) is increased when paste or mortar are present (D_c) and a corresponding reduction in aggregate volume is required to maintain concrete volumetric proportions.

Step 3—Determine required paste:

Option (a): For high-strength pervious concrete or pervious concrete placed with low compaction energy, multiply the amount of coarse aggregate determined in Step 2 by 0.24.

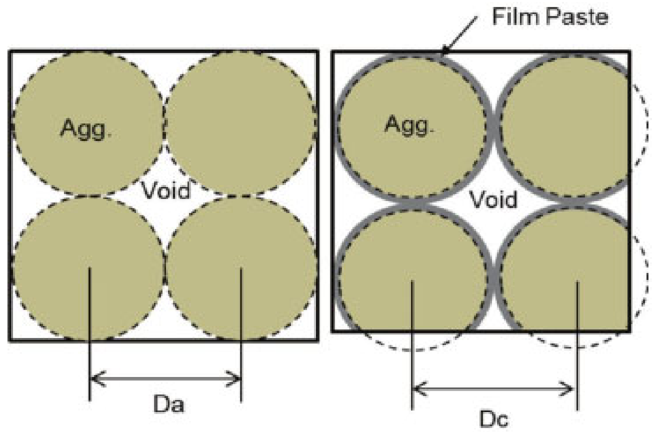

Fig 6.3a—Aggregate volume reduction required to accommodate paste coating thickness.

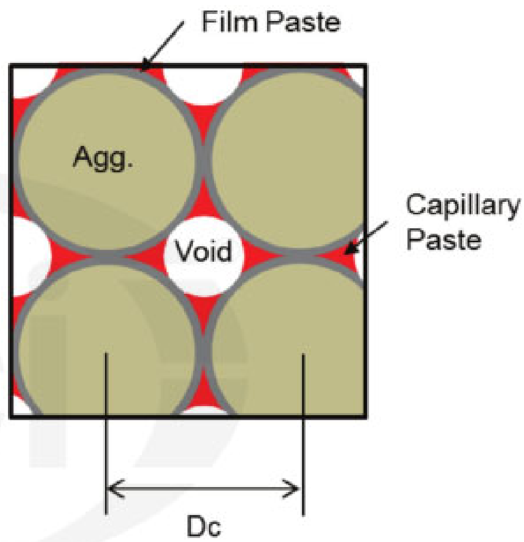

Fig 6.3b—Relationship between film paste coating and capillary paste.

Option (b): For low-strength pervious concrete or pervious concrete placed with high compaction energy, multiply the amount of coarse aggregate determined in Step 2 by 0.21.

For normalweight aggregates, research has shown that 5 to 7% sand by mass increases the film paste thickness, strength, and durability. The amount of paste and compaction energy influences how much capillary paste is required for strength and durability purposes (Fig. 6.3b).

Step 4—Select desired supplementary cementitious materials (SCMs): Fly ash, slag cement, and silica fume have all been successfully used in pervious concrete. Please refer to Chapters 4 and 5 for more discussion on replacement rates.

Step 5—Select *w/cm* and amount of water needed: Typical *w/cm* for pervious concrete range from 0.30 to 0.40.

Step 6—Select admixtures: Please refer to Chapters 4 and 5 for more discussion on the use of various admixtures. Common admixtures include water reducer, hydration control, air-entraining, and viscosity-modifying.

Step 7—Select fibers (if desired): A wide variety of fiber shapes and materials are available. Research has shown

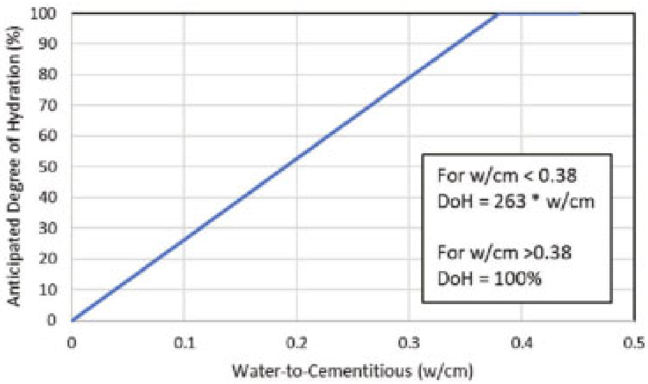

Fig 6.3c—Anticipated degree of hydration for various w/cm.

benefit for using many types within pervious concrete. In general, smaller fibers and lower dosages are used in light-duty applications, while larger fibers and higher dosages for more industrial applications. Some reported dosage rates include:

(a) Monofilament microfibers: 1.0 to 1.5 lb/yd³ (0.6 to 0.9 kg/m³)
(b) Fibrillated or cellulose fibers: 1.5 to 3.0 lb/yd³ (0.9 to 1.8 kg/m³)
(c) Macrofibers: 2.5 to 7.5 lb/yd³ (1.5 to 4.4 kg/m³)

Step 8—Determine trial mixture proportions, design hardened unit weight (DUW), and design void content (DVC): The design void content (DVC) is determined volumetrically from the selected mixture proportions. The DVC includes both entrained/entrapped air and water permeable voids. The design hardened unit weight (DUW) includes the cementitious materials, dry aggregate, and portion of water incorporated into hydration products. An assumed 100% degree of hydration (DoH) is assumed at *w/cm* above 0.38. If the actual cement chemistry is known, then the actual amount of water needed to hydrate the cementitious materials can be calculated. If that information is not known, then a good estimate to use is 25 lb (11.3 kg) of water will be chemically incorporated in the hydration of 100 lb (45.4 kg) of cement when the *w/cm* exceeds 0.38. If the *w/cm* is below 0.38, then sufficient channels and pores will not allow complete hydration and the amount of water incorporated within the cementitious paste will be reduced. Figure 6.3c shows the degree of hydration reduction (after Bentz et al. [2005]).

Example for *w/cm* of 0.35

0.35 × 263 = 92.1% anticipated DoH

92.1% × 25 lb/100 lb = 23.0 lb (10.4 kg) water anticipated to be incorporated into the hardened concrete

Step 9—Trial batch testing: Trial batch testing may be performed in the laboratory or the field. Because field compaction is difficult to simulate during lab placements, actual on-site placement will be the most representative for further iterations.

(a) Measure the fresh density according to ASTM C1688/C1688M. Because the compaction energy associated with ASTM C1688/C1688M will not match that of field compaction, the ASTM C1688/C1688M density should be used for quality control for variability on delivered proportions and workability and not compared with the DUW. Typical values range between 124 and 133 lb/ft³ (1990 to 2130 kg/m³).
(b) Core the samples and determine the hardened density according to ASTM C1754/C1754M.
(c) After determining the hardened density, determine vertical compaction variability and drain-down. Cut the hardened cylinders in half horizontally and determine the hardened density of the top and bottom portions individually. Density should not vary by more than 5%. Significantly higher density in the top half indicates poor workability for the desired compaction technique with increased susceptibility to bottom-up cracking. Significantly higher density in the bottom half indicates paste drain-down with increased susceptibility to clogging within the pervious concrete section.
(d) Determine raveling potential according to ASTM C1747/C1747M. Mass loss should be less than 40% for samples placed at the desired density.

Step 10—Adjust the mixture:

(a) If unit weight is low, increase the cementitious materials content, sand content, or admixtures to increase workability.
(b) If unit weight is high, decrease the cementitious materials content, sand content, or admixtures to decrease workability.
(c) If abrasion is high, increase fiber dosage, cementitious materials content, or admixtures to increase workability.

6.4—Mixture proportioning process examples

Example 1:

The following proportioning example is based on a mixture to be placed on a pedestrian plaza in Florida (no freezing and thawing concerns) that, because of site geometry, does not facilitate the use of a large roller screed. Placement will be performed using a straightedge and vibratory bullfloat. The mixture will contain crushed limestone coarse aggregate with a specific gravity of 2.40, absorption of 1.5%, and DRUW of 90 lb/ft³. The mixture will contain ASTM C150/C150M Type I cement (SG 3.15) and silica fume (SG 2.2).

Step 1—Select coarse aggregate: Per ASTM C29/C29M and the properties previously presented, the compacted voids are 39.9%, which exceed the required 38%.

Step 2—Determine required aggregate: Because no fine aggregate was desired due to the lack of freezing and thawing concerns and low loading, the DRUW paste modifier is 0.95.

90 lb/ft³ × 0.95 × 27 ft³/yd³ = 2187 yd³ coarse aggregate
(1440 kg/m³ × 0.95 = 1368 m³)
0 lb/yd³ fine aggregate

Step 3—Determine required paste: Because the site conditions dictate low compaction energy, the amount of paste needed is 0.24 × aggregate weight.

2309 lb/yd³ × 0.24 = 554 lb/yd³ total cementitious materials

Step 4—Select desired SCMs: The problem statement included silica fume as an SCM. Research specific to

pervious concrete has shown up to 5% to be appropriate and beneficial and as such, 5% is used in this example.

$$554 \text{ lb/yd}^3 \times 5\% = 28 \text{ lb/yd}^3 \text{ silica fume}$$

Step 5—Select *w/cm* and amount of water needed: Although a common range of *w/cm* for pervious concrete is 0.30 to 0.40, because silica fume is included, a *w/cm* of 0.37 will be selected for this example to help facilitate good workability and minimize paste shrinkage.

$$554 \text{ lb/yd}^3 \text{ total cementitious material} \times 0.37 = 205 \text{ lb/yd}^3 \text{ water}$$

Step 6—Select admixtures: Please refer to Chapters 4 and 5 for specifics on admixture selection. The following two admixtures and dosages have been selected from values commonly reported in the literature.

(a) Polycarboxylate mid-range water-reducing agent: 6 oz./cwt, 33 oz./yd^3

(b) Hydration-controlling admixture: 6 oz./cwt, 33 oz./yd^3

Step 7—Select fibers (if desired): No fibers will be used in this example.

Step 8—Determine trial mixture proportions, DUW, and DVC:

Component	lb/yd^3	ft^3/yd^3	%	Notes
Cement	526	67	9.9	
Silica fume	28	20	0.7	
Coarse aggregate	2309	15.42	57.1	
Water	205	3.29	12.2	
Design void content	—	5.42	20.1	

For the developed mixture, the DVC would be 20.1%, which is within the 20 to 25% common for pervious concrete. The DUW includes the amount of cementitious materials, dry aggregate, and water incorporated into the hydration products.

$$(526 \text{ lb/yd}^3 + 28 \text{ lb/yd}^3 + 2309 + 554 \text{ lb/yd}^3 \times 0.25 \times (263 \times 0.37)/100)/27 = 111.0 \text{ lb/yd}^3$$

Example 2:

The following proportioning example is based on a mixture to be placed in a freezing-and-thawing climate using a crushed limestone coarse aggregate with a specific gravity of 2.67, absorption of 0.5%, and DRUW of 98 lb/ft^3. A rounded river sand fine aggregate will be included with a specific gravity of 2.61 and absorption of 0.8%. The cementitious materials will include slag cement and silica fume and the mixture will include fibers. The pavement will be placed using a weighted roller screed and finishing with a vibrating float.

Step 1—Select coarse aggregate: Per ASTM C29/C29M and the properties previously presented, the compacted voids are 41.2%, which exceed the required 38%.

Step 2—Determine required aggregate: Because fine aggregate was desired due to freezing-and-thawing concerns and low loading, the DRUW paste modifier is 0.90. For normalweight aggregate, 5 to 7% fine aggregate provides good improvement to strength and durability.

$$98 \text{ lb/ft}^3 \times 0.90 \times 27 \text{ ft}^3/\text{yd}^3 = 2381 \text{ lb/yd}^3 \text{ coarse aggregate}$$

$$2381 \text{ lb/yd}^3 \times 5\% = 119 \text{ lb/yd}^3 \text{ fine aggregate}$$

Step 3—Determine required paste: Because the placement will use high compaction energy, the amount of paste needed is 0.21 × aggregate weight.

$$2381 \text{ lb/yd}^3 \times 0.21 = 500 \text{ lb/yd}^3 \text{ total cementitious materials}$$

Step 4—Select desired SCMs: The problem statement included slab cement and silica fume as SCMs. Research specific to pervious concrete has shown up to 5% to be appropriate and beneficial for silica fume and as such, 5% is used in this example along with a 25% replacement for slag cement.

$$500 \text{ lb/yd}^3 \times 5\% = 25 \text{ lb/yd}^3 \text{ silica fume}$$

$$500 \text{ lb/yd}^3 \times 25\% = 125 \text{ lb/yd}^3 \text{ slag cement}$$

Step 5—Select *w/cm* and amount of water needed: A common range of *w/cm* for pervious concrete is 0.30 to 0.40. Because a *w/cm* was not specified, a 0.35 will be selected as a starting point.

$$500 \text{ lb/yd}^3 \text{ total cementitious} \times 0.35 = 175 \text{ lb/yd}^3 \text{ water}$$

Step 6—Select admixtures: Please refer to Chapters 4 and 5 for specifics on admixture selection. The following three admixtures and dosages have been selected from values commonly reported in the literature.

1. Air-entraining agent: 2 oz./cwt, 10 oz./yd^3
2. Polycarboxylate mid-range water-reducing agent: 6 oz./cwt, 30 oz./yd^3
3. Hydration-controlling admixture: 6 oz./cwt, 30 oz./yd^3

Step 7—Select fibers (if desired): No fibers will be used in this example.

Step 8—Determine trial mixture proportions, DUW, and DVC:

Component	lb/yd^3	ft^3/yd^3	%	Notes
Cement	350	1.78	6.6	
Slag cement	125	0.77	2.9	
Silica fume	25	0.18	0.7	
Coarse aggregate	2381	14.3	54.1	
Fine aggregate	119	0.7	2.7	
Water	175	2.8	10.4	
Fibers	1.5	0.1	0.1	
Design void content	—	6.1	22.6	

For the developed mixture, the DVC would be 22.6%, which is within the 20 to 25% common for pervious concrete. The DUW includes the amount of cementitious materials, dry aggregate, and water incorporated into the hydration products.

$$(350\ \text{lb/yd}^3 + 125\ \text{lb/yd}^3 + 25\ \text{lb/yd}^3 + 2381 + 119 + 500\ \text{lb/yd}^3 \times 0.25 \times (263 \times 0.35)/100 + 1.5)/27 = 115.4\ \text{lb/yd}^3$$

CHAPTER 7—PERVIOUS PAVEMENT DESIGN

7.1—Introduction

Pervious pavement design needs to consider site design with thickness. In the thickness determination of a pervious pavement section, two important analyses should be conducted: one for structural adequacy and one for hydraulic characteristics. These two characteristics influence each other so they both should be addressed with care. The thicker resulting pavement cross section should be used. This chapter discusses both aspects.

7.2—Site design

Site design for pervious pavements requires a paradigm shift from historical impervious pavement designs. Instead of keeping the base dry under impervious pavements, pervious pavements store water in the reservoir layer. Instead of grading most of the site drainage toward the pavement, site design should direct stormwater runoff from landscaping areas and impervious surfaces away from the pervious pavement to protect the interconnect voids within the pervious pavement from sediment and clogging. Isolating the sediment sources can be accomplished from simple grade separations to construction of structures depending on the site.

7.3—Structural design

7.3.1 *Subgrade and subbase*—The subbase is the aggregate layer installed below the paving. The subgrade is the soil below the paving and the subbase. The subbase provides vertical support, storage capacity, and filtering ability for treatment of pollutants. Some soils may provide adequate support and drainage, so the subbase may be optional. If the support, draining abilities, or filtering abilities are limited by the subgrade, however, then a subbase material should be used. In areas exposed to freezing-and-thawing cycles, the rock subbase layer acts as insulation and provides a substantial lag in the formation of frost beneath pervious pavement (Bäckström 2000; Kevern and Schaefer 2008). The subgrade also provides vertical support for the paving. Increasing the stiffness of the subbase and subgrade increases the load capacity of a given paving system. Stiffness in the subgrade can be measured by the modulus of subgrade reaction, the California bearing ratio (CBR), or by a few other less common methods. Table 7.3.1a, developed from ACI 330R and Delatte (2014), provides typical stiffness values for

Table 7.3.1a—Recommended *k*-value ranges for various soil types (adapted from ACI 330R, AASHTO [1998], and Delatte [2014])

AASHTO Class	Description	ASTM/USCS class	Dry density, lb/ft³ (kg/m³)	CBR, %	*k*-value, psi/in. (MPa/m)
Coarse-grained soils					
A-1-a, well graded	Gravel	GW, GP	125 to 140 (2000 to 2240)	60 to 80	300 to 450 (81 to 122)
A-1-a, poorly graded			120 to 130 (1920 to 2080)	35 to 60	300 to 400 (81 to 108)
A-1-b	Coarse sand	SW	110 to 130 (1760 to 2080)	20 to 40	200 to 400 (54 to 108)
A-3	Fine sand	SP	105 to 120 (1680 to 1920)	15 to 25	150 to 300 (41 to 81)
A-2 soils (granular material with high fines)					
A-2-4, gravelly A-2-5, gravelly	Silty gravel Silty sandy gravel	GM	130 to 145 (2080 to 2320)	40 to 80	300 to 500 (81 to 136)
A-2-4, sandy A-2-5, sandy	Silty sand Silty gravelly sand	SM	120 to 135 (1920 to 2160)	20 to 40	300 to 400 (81 to 108)
A-2-6, gravelly A-2-7, gravelly	Clayey gravel Clayey sandy gravel	GC	120 to 140 (1920 to 2240)	20 to 40	200 to 450 (54 to 122)
A-2-6, sandy A-2-7, sandy	Clayey sand Clayey gravelly sand	SC	105 to 130 (1680 to 2080)	10 to 20	150 to 350 (41 to 95)
Fine-grained soils[*]					
A-4	Silt	ML, OL	90 to 105 (1440 to 1680)	4 to 8	25 to 165 (7 to 45)[*]
	Silt/sand/gravel mixture		100 to 125 (1600 to 2000)	5 to 15	40 to 220 (11 to 60)[*]
A-5	Poorly graded silt	MH	80 to 100 (1280 to 1600)	4 to 8	25 to 190 (7 to 51)[*]
A-6	Plastic clay	CL	100 to 125 (1600 to 2000)	5 to 15	25 to 255 (7 to 69)[*]
A-7-5	Moderately plastic elastic clay	CL, OL	90 to 125 (1440 to 2000)	4 to 15	25 to 215 (7 to 58)[*]
A-7-6	Highly plastic elastic clay	CH, OH	80 to 110 (1280 to 1760)	3 to 5	40 to 220 (11 to 60)[*]

[*]*k*-value of a fine-grained soil is highly dependent on degree of saturation.

different types of soils and provides correlations between the values calculated by the various methods.

Traditional pavement design attempts to exclude water from entering the subgrade below the pavement. In most cases, pervious paving is designed to encourage water to saturate the subgrade below paving. This condition should be considered when determining the properties for the subgrade. The more a soil is compacted, the less porous it becomes. For this reason, pervious paving subgrades are usually compacted to a lower density than subgrades for traditional concrete paving. The infiltration rate of the soil should be measured per ASTM D3385 to input into the hydrologic design. In some applications, such as pedestrian uses, subgrade compaction may not be necessary.

ASTM D1883 defines a laboratory method for determining the CBR of a given soil that includes an option for soaking the soil sample in water for 96 hours before testing. This option should be used for testing fine-grained soils that would be compacted to the compaction criteria established by the architect/engineer.

When specifying compaction for structural design, consideration should be given to the effect compaction has on the hydraulic properties of different soils. Compacting some clay soils to 90% may cause a large reduction in permeability, whereas compacting sandy soils to nearly 100% may only have a minor effect. It is important, therefore, to carefully examine the soils present on each project for both structural and drainage capacities before specifying a compaction range. Equally important is required field testing of the subgrade for permeability after compaction to confirm they still conform to structural and hydraulic calculations used for the site.

Expansive soils are soils that change volume when subject to changes in moisture content. Expansive soils can be mitigated by chemical treatment or by removing their upper layers and replacing them with non-expansive soil. The depth of soil replacement or soil treatment should be selected so the downward soil pressure provided by the shallow stable soil exceeds the expansive soil pressures generated by increases in the moisture content of the deeper soil. With lime stabilization, the permeability of a clayey soil is increased rapidly. Soils with higher clay contents and those compacted on the dry side of optimum tend to show greater increases in permeability with lime treatment. However, in some cases, permeability will decrease with age (Bell 1993). Soils treated with cement and fly ash show reduced permeability after application (Little et al. 2000). Depending on the application, reduced permeability might be desirable for applications such as water harvesting.

Table 7.3.1b—Effect of untreated subbases on *k*-values (PCA 1984; Delatte 2014)

Subgrade *k*-value, psi/in. (MPa/m)	Subbase thickness, in. (mm)			
	4 in. (100 mm)	6 in. (150 mm)	9 in. (225 mm)	12 in. (300 mm)
50 (13.5)	65 (17.5)	75 (20)	85 (23)	110 (30)
100 (27)	130 (35)	140 (38)	160 (43)	190 (51)
200 (54)	220 (60)	230 (62)	270 (73)	320 (87)
300 (81)	320 (87)	330 (89)	370 (100)	430 (117)

Some soils are subject to frost heaving. Soils located above the frost depth should be removed and replaced by soils that are not subject to frost heave. As indicted previously, an appropriate subbase has proven to be effective at protecting porous pavements from frost heaving.

Adding a granular aggregate subbase below the concrete paving increases the stiffness of the pavement support. Table 7.3.1b, developed from ACI 330R-08 Table 3.2 and Delatte (2014), indicates the increase in subgrade modulus provided by different thicknesses of subbase. This granular subbase can also be used as a reservoir for storing stormwater.

7.3.2 *Concrete strength*—Guidance for structural design of conventional concrete pavements is provided in ACI 330R for parking lots and in ACI 325.12R for streets and roads. These documents cover many different aspects of paving design. The structural design recommendations in these documents, however, are not necessarily applicable for use with pervious pavement. For example, the design tables in these two guides are based on a minimum concrete flexural strength of 500 psi (3400 kPa), and pervious concrete often has lower strength. As there are no standardized test methods for strength of pervious concrete, design and specification by concrete strength presents concerns. It is, however, possible to design based on strength estimates until adequate test methods become available.

The ACPA PerviousPave design program allows the engineer to design pervious pavements using either U.S. customary or SI units. The software may be used for hydrological design as well as structural design of pervious concrete pavements (ACPA 2014a).

For pervious concrete pavements, somewhat like conventional pavements, the structural design is carried out first, and then the drainage or hydrological system is designed. The thicker of the two resulting cross sections is used for the design.

Designing pervious concrete pavements based on fatigue presents a bit of a problem. At this time, there are no standardized testing methods for fatigue of pervious concrete, and little research has been done on the fatigue performance of the material. As a result, this design approach should be applied with caution for the time being. This caution is provided in both the PerviousPave software and the backing ACPA documentation (ACPA 2014a). The procedures can be updated when better information on fatigue of pervious concrete pavements becomes available.

In developing these design tables, concrete compressive strengths are assumed to be 2000, 3000, or 4000 psi (13.8, 20.7, or 27.6 MPa), corresponding to flexural strengths of 300 to 450, 400 to 550, and 500 to 650 psi (2.1 to 3.1, 2.8 to 3.8, and 3.5 to 4.5 MPa), respectively. There are currently no accepted test methods for the flexural strength of pervious concrete.

7.3.3 *Pavement thickness selection*—For a given concrete strength, pavement thickness selection is generally based on subgrade support (*k*-value) and traffic. Subgrade support values and adjustments for untreated bases are shown in

Table 7.3.3a—Street and parking lot traffic classifications from ACI 325.12R and ACI 330R (Delatte 2014)

Street/parking lot classification	VPD or ADT, two-way*	Heavy commercial vehicles (two axle, six tire, and heavier)		Category
		Percent	Trucks per day	
Car parking only		0	0	Residential
Truck access lanes			1 to 10	Residential
Light residential	200	1 to 2	2 to 4	Residential
Residential	200 to 1000	1 to 2	2 to 4	Residential
Shopping center entrance and service lanes, bus, truck parking			25 to 300	Collector
Collector	1000 to 8000	3 to 5	50 to 500	Collector
Bus, truck parking			100 to 700	Minor arterial
Minor arterial	4000 to 15,000	10	300 to 600	Minor arterial
Major arterial	4000 to 30,000	15 to 20	700 to 1500	Major arterial
Business	11,000 to 17,000	4 to 7	400 to 700	Major arterial
Industrial	2000 to 4000	15 to 20	300 to 800	Major arterial
Heavy truck parking			700	Major arterial

*Vehicles per day or average daily traffic.

Tables 7.3.1a and 7.3.1b. According to the ACPA (2014a) PerviousPave program, the *k*-value may be input directly, or the resilient modulus of the subgrade (MRSG) may be input in psi or MPa, as well as the properties of the reservoir layer or layers. One or two reservoir layers may be used, with layer inputs in inches or mm. Unless pervious pavements are placed directly on free-draining soils, reservoir base layers are almost always used. Therefore, the subgrade *k*-value is less important than for other light-duty pavements.

Traffic categories are defined by average daily truck traffic (ADTT). ACI 330R and Delatte (2014) provide a full discussion of this topic. The ADTT does not correspond to a single-sized truck axle load. It assumes a collection of truck sizes from small to large, with a high frequency of small trucks and a low frequency of large trucks. Because the heaviest trucks, even in small numbers, dominate the fatigue damage of pavement, they should be the basis for traffic category selection. The ACPA (2014a) PerviousPave traffic categories are: residential/parking lot; collector; shoulder for minor arterial; and shoulder for major arterial. The program assumes that the shoulders only carry 10% of the traffic that is carried by the mainline pavement. Traffic categories are provided in Table 7.3.3a.

Concrete pavement thickness design is also influenced by edge support. City streets often have curbs and gutters tied to the pavement edge and or placed integrally with the pavements. This reduces edge stresses and makes it possible to build thinner pavements. Curbs and gutters can be built first and used as side forms to construct street or parking lot pavements.

For the case where edge support is not provided, pavement thickness may be determined using Table 7.3.3b. Table 7.3.3c is for pavements with edge support. These were developed using PerviousPave and are based on a design life of 20 years.

As an example, consider a collector road with one-way average daily traffic (ADT) of 1000 vehicles, with 5% trucks, or 50 trucks per day. The subgrade is an SC, or sandy A-2-6 or A-2-7 soil, with CBR = 10 to 20 and *k*-value of 150 psi/in. (41 MPa/m). With 8 in. (200 mm) of crushed stone subbase, this may be adjusted to a *k*-value of 200 psi/in. (54 MPa/m) by interpolation of Table 7.3.1b. There is a concrete curb and gutter, and the estimated flexural strength of the pervious concrete is 400 psi (2.8 MPa). From Table 7.3.3c, the required pavement thickness is 7.5 in. (191 mm). Further discussion of this design example is provided by Delatte (2014).

One alternative for handling heavier traffic while retaining the benefits of a pervious concrete pavement is to combine the pervious concrete with conventional pavement, either concrete or asphalt. In a parking lot, the parking stalls may be made of pervious concrete while the rest of the pavement is asphalt or concrete, which drains onto the parking stalls. Another alternative that has been used for four-lane city streets is to pave the inner traffic lanes with conventional concrete that drains onto the outer parking lanes that are made of pervious concrete. In these cases, the pervious concrete should be designed to handle not only the rain that falls onto it, but also the runoff from adjacent impervious surfaces. This may also increase the risk of clogging the pervious concrete with debris if not cleaned regularly (Delatte 2014). Cleaning is discussed in Section, 8.10, Maintenance.

7.4—Stormwater management design

7.4.1 *General*—The major benefit of pervious concrete is its hydrological performance. While regulations vary among state stormwater agencies, local regulations often determine how benefits can be derived from the hydrologic performance of pervious concrete. Even within different geological areas within a given city's limits, the regulations have been known to change. The basics of the technology are the same, however, regardless of geographic area.

Table 7.3.3b—Pavement thickness design table, no edge support (Delatte 2014)

CBR = 2		Pervious concrete flexural strength			
50 psi/in. (13.5 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	7 (180)	7.5 (190)	8.5 (215)	9 (230)
	10	8 (200)	8.5 (215)	9 (230)	10 (255)
Collector	25	9 (230)	9.5 (240)	10 (255)	11 (280)
	300	9.5 (240)	10.5 (275)	11.5 (290)	12.5 (320)
Minor arterial shoulder	100	9.5 (240)	10 (255)	11 (280)	12 (305)
	300	10 (255)	10.5 (275)	11.5 (290)	12.5 (320)
	700	10.5 (275)	11 (280)	12 (305)	13 (330)
Major arterial shoulder	700	11 (280)	12 (305)	13 (330)	14 (355)
	1500	11.5 (290)	12 (305)	13 (330)	14.5 (370)
CBR = 3		Pervious concrete flexural strength			
100 psi/in. (27 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	6.5 (165)	7 (180)	7.5 (190)	8 (200
	10	7.5 (190)	8 (200)	8.5 (215)	9 (230)
Collector	25	8 (200)	8.5 (215)	9.5 (240)	10 (255)
	300	9 (230)	9.5 (240)	10.5 (275)	11 (280)
Minor arterial shoulder	100	8.5 (215)	9 (230)	10 (255)	11 (280)
	300	9 (230)	9.5 (240)	10.5 (275)	11.5 (290)
	700	9.5 (240)	10 (255)	11 (280)	12 (305)
Major arterial shoulder	700	10 (255)	10.5 (275)	11.5 (290)	12.5 (320)
	1500	10.5 (275)	11 (280)	12 (305	13 (330)
CBR = 6		Pervious concrete flexural strength			
150 psi/in. (40.5 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	6 (150)	6.5 (165)	7 (180)	8 (200)
	10	7 (180)	7.5 (190)	8 (200)	9 (230)
Collector	25	7.5 (190)	8 (200)	9 (230)	9.5 (240)
	300	8.5 (215)	9 (230)	9.5 (240)	10.5 (275)
Minor arterial shoulder	100	8 (200)	8.5 (215)	9.5 (240)	10.5 (275)
	300	8.5 (215)	9 (230)	10 (255)	10.5 (275)
	700	9 (230)	9.5 (240)	10.5 (275)	11 (280)
Major arterial shoulder	700	9.5 (240)	10 (255)	11 (280)	12 (305)
	1500	9.5 (240)	10.5 (275)	11 (280)	12.5 (320)
CBR = 10		Pervious concrete flexural strength			
200 psi/in. (54 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	6 (150)	6.5 (165)	7 (180)	7.5 (190)
	10	6.5 (165)	7 (180)	7.5 (190)	8.5 (215)
Collector	25	7.5 (190)	8 (200)	8.5 (215)	9.5 (240)
	300	8 (200)	8.5 (215)	9.5 (240)	10.5 (275)

Table 7.3.3b, cont.—Pavement thickness design table, no edge support (Delatte 2014)

	100	8 (200)	8.5 (215)	9 (230)	10 (255)
Minor arterial shoulder	300	8.5 (215)	9 (230)	9.5 (240)	10.5 (275)
	700	8.5 (215)	9 (230)	10 (255)	11 (280)
Major arterial shoulder	700	9 (230)	9.5 (240)	10.5 (275)	11.5 (290)
	1500	9.5 (240)	10 (255)	11 (280)	12 (305)
CBR = 26		Pervious concrete flexural strength			
300 psi/in. (81 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	5.5 (140)	6 (150)	6.5 (165)	7 (180)
	10	6.5 (165)	7 (180)	7.5 (190)	8 (200)
Collector	25	7 (180)	7.5 (190)	8 (200)	9 (230)
	300	7.5 (190)	8.5 (215)	9 (230)	10 (255)
Minor arterial shoulder	100	7.5 (190)	8 (200)	8.5 (215)	9.5 (240)
	300	8 (200)	8.5 (215)	9 (230)	10 (255)
	700	8 (200)	8.5 (215)	9.5 (240)	10.5 (275)
Major arterial shoulder	700	8.5 (215)	9 (230)	10 (255)	11 (280)
	1500	9 (230)	9.5 (240)	10.5 (275)	11 (280)

Table 7.3.3c—Pavement thickness design table, supported edges (Delatte 2014)

CBR = 2		Pervious concrete flexural strength			
50 psi/in. (13.5 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	6 (150)	6.5 (165)	7 (180)	7.5 (190)
	10	7 (180)	7.5 (190)	8 (200)	8.5 (215)
Collector	25	7.5 (190)	8 (200)	8.5 (215)	9.5 (240)
	300	8.5 (215)	9 (230)	9.5 (240)	10.5 (275)
Minor arterial shoulder	100	8 (200)	8.5 (215)	9.5 (240)	10 (255)
	300	8.5 (215)	9 (230)	10 (255)	10.5 (275)
	700	9 (230)	9.5 (240)	10 (255)	10.5 (275)
Major arterial shoulder	700	9.5 (240)	10 (255)	11 (280)	12 (305)
	1500	9.5 (240)	10.5 (275)	11 (280)	12 (305)
CBR = 3		Pervious concrete flexural strength			
100 psi/in. (27 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	5.5 (140)	6 (150)	6.5 (165)	7 (180)
	10	6 (150)	6.5 (165)	7 (180)	8 (200)
Collector	25	7 (180)	7.5 (190)	8 (200)	8.5 (215)
	300	7.5 (190)	8 (200)	9 (230)	9.5 (240)
Minor arterial shoulder	100	7.5 (190)	8 (200)	8.5 (215)	9 (230)
	300	8 (200)	8.5 (215)	9 (230)	9.5 (240)
	700	8 (200)	8.5 (215)	9.5 (240)	10 (255)
Major arterial shoulder	700	8.5 (215)	9 (230)	10 (255)	10.5 (275
	1500	9 (230)	9.5 (240)	10 (255)	11 (280)

Table 7.3.3c, cont.—Pavement thickness design table, supported edges (Delatte 2014)

CBR = 6		Pervious concrete flexural strength			
150 psi/in. (40.5 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	5 (125)	5.5 (140)	6 (150)	6.5 (165)
	10	6 (150)	6.5 (165)	7 (180)	7.5 (190)
Collector	25	6.5 (165)	7 (180)	7.5 (190)	8 (200)
	300	7 (180)	7.5 (190)	8.5 (215)	9 (230)
Minor arterial shoulder	100	7 (180)	7.5 (190)	8 (200)	9 (230)
	300	7.5 (190)	8 (200)	8.5 (215)	9.5 (240)
	700	7.5 (190)	8 (200)	9 (230)	9.5 (240)
Major arterial shoulder	700	8 (200)	8.5 (215)	9.5 (240)	10 (255)
	1500	8.5 (215)	9 (230)	9.5 (240)	10.5 (275
CBR = 10		Pervious concrete flexural strength			
200 psi/in. (54 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	5 (125)	5.5 (140)	6 (150)	6.5 (165)
	10	5.5 (140)	6 (150)	6.5 (165)	7 (180)
Collector	25	6.5 (165)	6.5 (165)	7.5 (190)	8 (200)
	300	7 (180)	7.5 (190)	8 (200)	9 (230)
Minor arterial shoulder	100	6.5 (165)	7 (180)	8 (200)	8.5 (215)
	300	7 (180)	7.5 (190)	8 (200)	9 (230)
	700	7.5 (190)	8 (200)	8.5 (215)	9.5 (240)
Major arterial shoulder	700	8 (200)	8.5 (215)	9 (230)	10 (255)
	1500	8 (200)	8.5 (215)	9.5 (240)	10 (255)
CBR = 26		Pervious concrete flexural strength			
300 psi/in. (81 MPa/m)		450 psi (3.1 MPa)	400 psi (2.8 MPa)	350 psi (2.4 MPa)	300 psi (2.1 MPa)
Traffic	ADTT	Required pavement thickness, in. (mm)			
Residential/parking lot	1	5 (125)	5 (125)	5.5 (140)	6 (150)
	10	5.5 (140)	5.5 (140)	6 (150)	7 (180)
Collector	25	6 (150)	6.5 (165)	7 (180)	7.5 (190)
	300	6.5 (165)	7 (180)	7.5 (190)	8.5 (215)
Minor arterial shoulder	100	6.5 (165)	7 (180)	7.5 (190)	8 (200)
	300	6.5 (165)	7 (180)	8 (200)	8.5 (215)
	700	7 (180)	7.5 (190)	8 (200)	9 (230)
Major arterial shoulder	700	7.5 (190)	8 (200)	8.5 (215)	9.5 (240)
	1500	7.5 (190)	8 (200)	9 (230)	9.5 (240)

Attempts have been made to reduce the impact of urbanization by reducing stormwater runoff volumes to predevelopment levels and treating stormwater before it leaves the site. In the United States, the National Pollution Discharge Elimination System (NPDES) requires treatment of all stormwater to reduce the pollutant levels of the water. This is an empirical science, not nearly as exact as treatment of drinking water supplies due to the variability of the pollutant loads and flows. The technology is not intended to purify water to a potable state because it is not practical, economical, or necessary. The intent is only to remove as much pollutant load as possible to discharge cleaner water consistently and reduce the impact of urbanization on water supplies.

Water supplies typically fall into two categories: surface water and groundwater. Site development on sandy soils with deep groundwater deposits may follow a design philosophy of infiltration: discharging water to the groundwater table as cleanly as possible with discharge to surface water bodies only in heavy storm events. When site development is on clayey or silty soils, or in regions of shallow bedrock, the site drainage should typically treat the water before

Table 7.4.1.2—In-place pervious concrete pollutant removal studies compared to impervious pavement

Study	Location	Rain events sampled	C or M	TSS	TP	TN	Pb	Zn	Cu
Rushton (2001)	Tampa, FL	12 to 30	C	26 to 28	39 to 56	31 to 62	58 to 69	36 to 53	58 to 67
Drake et al. (2012)	Vaughan, ON	30 to 45	C	79	—	—	–5	87	49
Selbig and Buer (2018)	Madison, WI	43	M	59	23	—	—	—	—
Selbig et al. (2019)	Madison, WI	84	M	65	43	—	59	52	49
Pilon et al. (2019)	Alcoa, TN	5	C	97	—	—	—	31	—

Notes: C = reductions in pollutant concentrations measured; M = reductions in pollutant mass measured; TSS = total suspended solids; TP = total phosphorous; TN = total nitrogen; Cd = cadmium; Pb = lead; Zn = zinc; Cu = copper negative value indicates contribution.

running off site to merge with a surface water body such as a stream, river, or lake. On these low-permeability soils, however, some water infiltrates during every storm, just as it does in high-permeability soils; only the amount is less. The cumulative effect on recharge and water-quality treatment over the course of a year can be considerable.

7.4.1.1 There are three specific design features of pervious concrete that the designer may benefit from: 1) reduced runoff volume; 2) reduced treatment volume; and 3) reduced impervious area on the site.

7.4.1.1.1 *Reduced runoff volume*—Reduced runoff volume is the amount of stormwater that developed property would discharge to an adjacent land or water body in excess of the predevelopment discharge volume. Such BMPs include retention ponds, detention ponds, underdrains, swales, and wetlands. Most of these BMPs consume valuable, developable real estate. By eliminating or reducing the size of these facilities, a project can be more profitable to the owner. This may reduce the amount of real estate necessary or increase the amount of income generating space.

7.4.1.1.2 *Reduced treatment volume*—Reduced treatment volume is the quantity of stormwater that should be held on site and treated before leaving the property. Treatment may occur through a combination of chemical, physical, and biological processes depending on the BMP type.

7.4.1.1.3 *Reduced impervious area*—Reduced impervious area is the fraction of the land area that does not allow infiltration of rainfall at the start of a rainfall event; this usually consists of buildings and pavements. Many municipalities limit the amount of impervious area allowed on a given project site.

7.4.1.2 The use of pervious concrete pavements as a retention or infiltration system BMP is effective for improving runoff water quality and reducing runoff volume when properly maintained (Table 7.4.1.2). The St. Johns River Water Management District (1999), for example, defines retention to include pervious pavement with subgrade.

Reduction in drainage facilities from reduced runoff volumes using pervious concrete has an economic benefit to the developer. This economic benefit can be evaluated by comparing the price of building a pervious concrete parking lot to building a pond with drainage structures and buying the associated land.

For a more thorough discussion of stormwater treatment BMPs, refer to St. Johns River Water Management District (1999). For general information on stormwater hydrology not linked to specific jurisdictions, refer to Ferguson (1994, 1998) and Debo and Reese (2002).

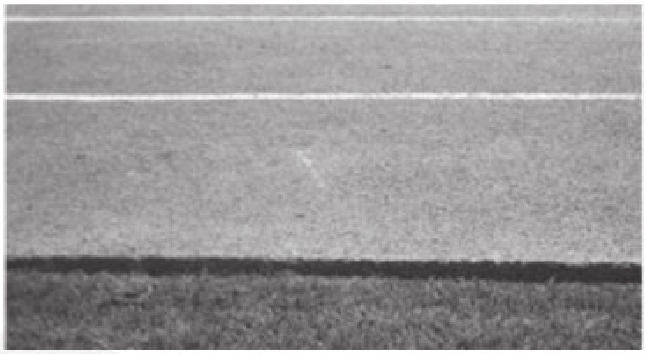

Fig. 7.4.2—Example of landscaped area at lower elevations than pervious concrete pavement.

7.4.2 *Reducing clogging potential*—The designer of a pervious concrete pavement can reduce clogging potential by ensuring that the design of the site:

(a) Shows landscaped areas at lower elevations than the pervious concrete pavement (Fig. 7.4.2), reduces to a minimum the slope of the landscaped areas when lower elevations are not possible, and includes a curb to isolate landscaped areas that are at higher elevations than the pavement.

(b) Minimizes soil erosion of disturbed areas. Bare soil in these areas should be avoided and the use of permanent pasture and brush cover are recommended. Special control measures, such as silt fences, should always be used during construction.

(c) Prevents vehicles from driving from unpaved areas onto the pervious concrete pavement.

(d) Does not lay in the path of wind from nearby unpaved areas, beachfronts, or deserts and limits the amount of stormwater flowing onto the pervious concrete from adjacent, conventional (not pervious) pavements and landscaped areas unless it can be shown that:

i. The volume of water from the conventional pavement will be free of sediments

ii. The pervious subbase has been designed to handle the water from the combined areas

iii. Sufficient pervious concrete surface area to catch leaves, litter, or other debris that may prematurely clog the pervious concrete between maintenance periods

7.4.3 *Drainage design*—Runoff is estimated through the use of many accepted methods. Two of the more common tools are the rational method and the soil conservation service (SCS) curve number. With either method, the designer should consider in the runoff analysis a variety of input and output variables such as absorption, evaporation, rainfall intensity, infiltration, and duration of the storm. Each of these variables will have an impact on the runoff volume and the treatment volume necessary for the site.

The rational method uses a coefficient to determine the peak runoff rate for a given rainfall intensity and drainage area. The runoff coefficient C accounts for land use, soil type, and slope of the area. Typical values for C range from 0.05 for a flat lawn on a sandy soil to 0.95 for a rooftop.

Other types of pervious pavements have been assigned runoff coefficients ranging from 0.65 to 0.95. For a pervious pavement, the underlying soil type and its permeability will have an impact on the runoff coefficient. In each rain event, the underlying soil type and its permeability will have an impact on the runoff coefficient. A well-maintained pervious pavement will typically drain faster than the subgrade soils, which limit the infiltration rate of the system.

Research (Wimberly et al. 2001) indicates that for certain pervious concrete system designs—particularly those over well-drained subgrades and subbases—the runoff coefficient for pervious concrete is negligible for 2- to 5-year storms, and as low as 0.35 for 100-year storms.

Other studies (Haselbach and Freeman 2006) also indicate that there will be reduced infiltration for systems overlain with sandy soils but that the expected runoff coefficients will still be very low for most storms.

Das (1993) showed that as the density of a soil increases, the rate of infiltration, and thus the permeability of the soil, decreases significantly. A decrease in the permeability of a soil would therefore justify an increase in the rational coefficient for a given design. Subgrade soils for a pervious concrete pavement should, therefore, be compacted uniformly and sufficiently to provide proper pavement support, but not be over-compacted to reduce the permeability of the soils and increase the rational coefficient. The Florida Concrete and Products Association (1990) recommends compacting sandy subgrade soils to a minimum density of 92 to 96% of maximum dry density per AASHTO T 180. In other parts of the United States, for other soil types, the compaction practices are different. Glacial tills have been compacted to 90 to 95% of the standard proctor; in the Carolinas, compaction has been to 92% of the modified proctor; and in Georgia, fine-grained soils are commonly compacted to 95% of standard proctor. In this situation, it may be necessary to add an open-graded aggregate subbase (or recharge bed) to the pavement system to compensate for the softness of subgrade soil, with the benefit of added retention volume.

With the SCS method (Soil Conservation Service 1986), soils are classified into hydrologic soil groups (HSGs) to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting. The HSGs—A, B, C, and D—are one element used in determining runoff curve numbers. A-type soils have the highest permeability, with each letter designation having lower permeability in B, C, and D soils.

This soil designation, in combination with the land cover, will identify a curve number (CN). The CN value tells the designer which curve to reference to determine the runoff volume for a given storm event. This method is more commonly used for generating a full hydrograph rather than just estimating peak flows. Pervious concrete pavements have been assigned CNs ranging from 60 to 95. Once again, the subgrade soil type, degree of compaction, and resulting permeability have an impact on the CN and, thus, on the drainage properties of the system.

When designing a pervious pavement system, such as a retention or an infiltration system, the volume of both the pavement and subbase should be considered (Paine 1990). For example, consider a section of pervious concrete with 20% void space. In a 6 in. (150 mm) thick pavement section, this void space is sufficient to hold more than 1 in. (25 mm) of stormwater. Additionally, if the pervious concrete is placed on a 6 in. (150 mm) section of a crushed stone subbase, the total capacity of the system increases to approximately 2-1/2 in. (65 mm). The minimum thickness of the pervious concrete pavement will be determined by the structural needs of the pavement system. It may be necessary, however, to build a thicker pervious concrete layer or subbase layer to increase stormwater storage capacity, but this may not be the most economical solution. If further capacity is necessary, storage may be added above the pavement surface in a curbed parking area (Fig. 7.4.3).

Other ways pervious pavements have been designed to treat stormwater include the use of an underdrain system. In this method, groundwater recharge may be limited due to site soil conditions. The pervious pavement is placed over a perforated pipe that is laid in a bed surrounded by an open-graded aggregate. Stormwater infiltrates through the pavement, through the gravel, and finds its way into the pipe. From there, the treated stormwater is discharged into a receiving water body. Treatment efficiencies for this

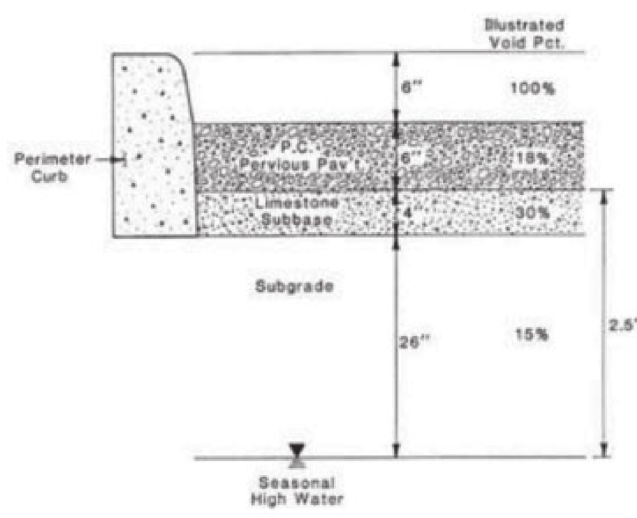

Fig. 7.4.3—Schematic of pervious concrete pavement designed as stormwater retention system. (Note: 1 in. = 25.4 mm.)

system average 66%. Additionally, there will be some direct recharge of the groundwater that will reduce the total runoff by as much as 33% (FCPA 1990) These percentages will vary depending on soil type.

Further groundwater recharge systems may include the use of drilled shafts backfilled with an open-graded aggregate, passing through clayey soils to more permeable strata. A typical design for this system might include a layer of an open-graded aggregate subbase for the pervious concrete pavement laying on the fine-grained site soils. The shafts would be spaced regularly to provide sufficient recharge capacity. The subgrade would have to be sloped to provide positive drainage to the shafts. Treatment efficiencies for this system would be expected to be similar to the underdrain design. Recharge rates, however, would be expected to be much higher.

Several other designs have been used to pass excess water-quality volume, increase storage capacity, or increase treatment volume. These include:

(a) Placing a perforated pipe at the top of a crushed stone reservoir to pass excess flow after the reservoir is filled
(b) Providing surface detention storage in a parking lot, adjacent swale, or detention pond with suitable overflow conveyance
(c) Adding a sand layer and perforated pipe beneath a recharge bed for filtration of the water-quality volume
(d) Placing an underground detention tank or vault system beneath the layers to store the treated water for reuse

Evaporation is another important factor in the calculation of water storage. Research shows that water stored in the pervious pavement and subbase may evaporate (Wanielista et al. 2007).

All the intricacies of a stormwater drainage design using pervious concrete pavement will be strongly tied to local practices and regulations. Refer to 7.4.3.3 for a sample set of design calculations that has been published by the Florida Concrete and Products Association (1990). Always review the full text and local stormwater regulations.

Designers may want to consider adding redundant drainage if the elevation of the finished paving surface is close to any areas that would be significantly impacted by occasional inundation. This can be as simple as grading the pavement to gently slope away from a building.

In addition to runoff, the designer should approximate pollution loads, including their nature and approximate range of concentration. This information, combined with the necessary hydrograph, will allow the designer to determine the appropriate size and design of the stormwater management system.

7.4.3.1 *Design equations and software*—As with conventional pavements, the hydrological design is carried out after the structural design. At present, two procedures are available for the hydrological design of pervious pavements. The procedure used in PerviousPave is based on the Los Angeles County Method, which assumes that the subbase/reservoir layer is designed to hold the entire volume of runoff water.

The PerviousPave program uses the Los Angeles County Method for hydraulic design (Rodden et al. 2010; ACPA 2014a). The total volume V of water (in cubic meters or cubic feet) to be drained by a pervious concrete pavement may be calculated as

$$V = (A_p + A_b) \times I \tag{7.4.3.1a}$$

The Los Angeles County Method equation for determining the required area of the pervious concrete is

$$A_p = \frac{V}{r_s \times h_s} \tag{7.4.3.1b}$$

This is a conservative approach, which assumes that all the rainfall is held within the reservoir layer. If some of the water is held within the pervious concrete, or by ponding on top of the pervious concrete with a curb, the equation should be modified as follows

$$A_p = \frac{V}{h_{curb} + r_c \times h_c + r_s \times h_s} \tag{7.4.3.1c}$$

Because the area of the pervious concrete is typically governed by the site design, and the thickness of the pervious concrete is determined from the structural design, the key parameter here to be selected is the thickness of the subbase or reservoir layer h_s. Solving Eq. (7.4.3.1c) for this layer thickness

$$h_s = \frac{1}{r_s}\left(\frac{V}{A_p} - h_{curb} - r_c \times h_c\right) \tag{7.4.3.1d}$$

It is also necessary to check that the detention time, typically 24 hours, is not exceeded. The calculated detention time, in hours, is

$$t_d = \frac{V}{A_p \times E} \tag{7.4.3.1e}$$

Recommended E values are 1/2 to 1 in. (13 to 25 mm) per hour for sandy soils, 0.1 in. (2.5 mm) per hour for silty soils, and 0.01 in. (0.25 mm) per hour for clayey soils (ACPA 2014a). If the system is very sensitive to infiltration, it may be necessary to test the soil in the field per ASTM D3385.

This procedure is conservative because it assumes that first the reservoir should hold the entire volume of rainfall, and only then does it begin to drain out. In reality, of course, the water infiltrates into the soil below while the rain is falling, and thus the actual requirement for thickness of the reservoir layer should be less.

7.4.3.2 *Considerations for sloping pavements*—Conventional pavements are usually sloped for drainage. In contrast, for pervious concrete pavements, cross slopes and crowns are not necessary because the water goes into the pavement instead of running over the top. The ACPA (2014b) provides a discussion of slope considerations to supplement the PerviousPave program. Pervious pavements have been placed successfully with slopes up to 16%. In some cases, transverse trenches (or other check dam designs) with drainpipes can be placed across the slope.

In fact, because of the rapid flow of water through a pervious pavement, it is possible for the water to flood out of the low side of a slope. Therefore, a slope reduces the available storage volume of a pervious concrete pavement. The effective storage volume may be calculated using Eq. (7.4.3.2a) (ACPA 2014b)

$$\text{Effective volume (\%)} = \frac{d}{2 \times s \times L} \times 100 \quad (7.4.3.2a)$$

For example, for a 100 ft (30 m) long pavement 12 in. (300 mm) thick, consisting of a 6 in. (150 mm) thick surface layer and a 6 in. (150 mm) thick reservoir, on a 1% slope, the effective volume would be

$$\text{Effective volume (\%)} = \frac{h_c}{2 \times s \times L} = \frac{0.3}{2 \times 0.01 \times 30} \times 100 = 50\%$$

Therefore, pervious concrete pavements should be as level as possible to maximize storage volume. Otherwise, it may be necessary to increase the thickness of the reservoir layer. Another option is to provide a recharge bed or a well at the toe of the slope. It is also possible to terrace the reservoir layer or provide check dams (ACPA 2014b).

7.4.3.3 *Design examples*

Example 1: Florida Concrete and Products Association (1990)

Given:

The pavement should store the first 1/2 in. (13 mm) of untreated runoff and recover that volume within a 72-hour period following a storm.

The storage volume V_r required in the pervious pavement may be calculated as

$$V_r = \text{rainfall (in.)} \times A \text{ (acre)} \times 43{,}560 \text{ (ft}^2\text{/acre)} \times 1 \text{ (ft)/12 (in.) (ft}^3) \quad (7.4.3.3a)$$

$$V_r = \text{rainfall (mm)} \times A \times 1 \text{ (m)/1000 (mm) (m}^3)$$

for a 1/2 in. (13 mm) first flush, then

$$V_r = 1/2\text{(in.)} \times A \times 43{,}560 \text{ (ft}^2\text{/acre)} \times 1 \text{ (ft)/12 (in.)} = 1815A \text{ (ft}^3)$$

$$V_r = 13 \text{ (mm)} \times A \times 1 \text{ (m)/1000 (mm)} = 0.013A \text{ (m}^3)$$

The Florida Concrete and Products Association (1990) suggests that the storage capacity of a pervious pavement system on sandy subgrade soils should include the void space of the soil above the seasonal high groundwater table and any storage of the pervious concrete pavement. This storage volume may be calculated as follows

$$V_p = A \times d_1 \times p_1/100 \quad (7.4.3.3b)$$

$$V_s = A \times d_2 \times p_2/100 \quad (7.4.3.3c)$$

This is essentially the same as the Los Angeles County method.

Upon completion of calculating the required water-quality storage volume V_r and deducting the subgrade soil volume V_s and available pavement storage volume V_p, the net difference will either be negative, indicating the requirements are met, or positive, indicating that additional storage is necessary. A granular subbase, such as an ASTM C33/C33M No. 57 material with a void space of 30% or greater, could provide additional storage. The area above the pavement is available for storage as well. The designer is cautioned that when applying this design technique, however, the water height for the infrequent design storm may cause the water to rise above the pavement surface. The pavement elevation should be lower than adjacent building floor elevations to avoid flood damage.

The Florida Concrete and Products Association (1990) gives further design examples for calculating the retention capacity of a parking area, runoff quantity, and recovery time. Some of these calculations are also given as examples in Atlanta Regional Commission (2001).

Example 2: Delatte (2014)

This example follows the previous structural design. The pervious pavement has a total area of 16,000 ft² (1486 m²) and drains a nonpervious area of 32,000 ft² (2972 m²), consisting of roofs, hardscapes, and other nondraining surfaces. Thus, the ratio of drained nonpervious area to pervious area is 2 to 1. The infiltration rate of the soil is 1/2 in. (12.7 mm) per hour, which would be on the low end for a sandy soil. Silts and clays would typically have much lower soil infiltration rates.

The water is not allowed to pond on the pavement surface, and the pervious concrete surface layer is not included as part of the hydrological design. These would be typical for a climate where freezing and thawing are likely. The reservoir layer is assumed to have 40% voids.

The design storm precipitation should be based on the location of the pavement and should be the 24-hour precipitation with either a 2- or 10-year return period. In the United States, these may be obtained through the National Oceanic and Atmospheric Administration. The PerviousPave program provides 2- and 10-year storms for many cities in the United States. For Cleveland, OH, USA, the 2-year storm is 2.34 in. (59 mm). The maximum detention time is usually set to 24 hours.

The results from the PerviousPave program are that the volume of water to be processed is 9360 ft³ (265 m³) and the minimum reservoir layer required is 17.6 in. (446 mm), which is more than the 8 in. (200 mm) provided.

There are a few options. The thickness of the reservoir could be increased, which in most cases would probably be the most economical approach. The size of the pervious pavement could be increased, or the size of the nonpervious area draining onto it could be reduced. Alternatively, other measures could be used to handle some of the stormwater, or curb detention could be used to handle the additional overflow.

7.5—Other considerations

The properties of in-place pervious pavement are highly variable and subject to the skill and experience of the installation contractor and the concrete supplier. The concrete properties used for design should be calibrated to local experience whenever practical, but due to the specialized nature of the product and the need for qualified installers, it may be advantageous to seek regional installers until qualified local installers become proficient with the product.

Pervious pavement is usually placed, then screeded and compacted. As pavement thickness is increased beyond 8 in. (200 mm), it becomes difficult to compact the full cross section of the pavement with uniform results due to a limited depth of influence of the roller. The top of the pavement will become more compacted than the bottom of the pavement. Because the strength of the pavement is increased with increased density, the design of the concrete section should consider this reduced strength at the base of the paving. At a concrete plant in Oregon, four 10 in. (250 mm) porous pavements were cut into beams to measure the difference in flexural strength between the compacted top and bottom half of the pavement. The results showed that while the top flexural strengths varied from 310 to 485 psi (2.14 to 3.34 MPa), the bottom portion of the test panels had a lower flexural strength of 272 to 275 psi (1.88 to 1.90 MPa). While this is a very limited test, it does show the noncompacted area of the pavement was consistent and that significant strength gain can be achieved by using compaction (Erickson 2006).

The void structure of a pervious concrete mixture not only allows for the vertical transmission of water, but it will also allow horizontal flow. This unique ability should be considered in establishing the drainage profiles. The vertical rate of flow is dependent on the permeability of the subgrade and on the thickness and porosity of the pavement. To the greatest extent possible, parking area profiles should be graded without slope. This will allow increased time for the subgrade to absorb and transmit water to the lower strata and reduce the horizontal flow rate. Where conditions do not allow for flat grades, the designer may consider providing impervious barriers transverse to the direction of horizontal flow. These barriers can be installed by increasing the consolidation of the pavement strip along the edge of transverse construction joints. The increased consolidation closes the void structure at this location. Installing transverse strips of normal impervious concrete reduces lateral flow in the down-grade direction. Curbs around the perimeter of the paved area also assist in reducing lateral flow rates, as well as meeting the stormwater retention requirements. Subbase erosion and damage to the pavement can occur if insufficient steps are taken to control the volume and velocity of the water flowing through the subbase and subgrade. Edge curbs or other structures to prevent this erosion should be constructed along all areas where the potential exists for water to flow under the pavement.

7.5.1 *Pervious pavement maintenance*—One nonstructural component that can help ensure proper maintenance of pervious concrete pavement is a carefully worded maintenance agreement that provides specific guidance, including how to conduct routine maintenance and surface repairs or rehabilitations. Signs should ideally be posted on the site that identifies pervious concrete pavement areas. Such signs should direct maintenance crews to the local NPDES enforcement authority and might read, "Pervious concrete pavement is used on this site to reduce pollution. Heavy vehicles prohibited. Do not resurface with nonpervious material. Call XXX-XXX-XXXX for more information."

Designers can account for the clogging potential of pervious concrete pavement in their drainage design. If a site is designed for a government facility, such as a stormwater utility with an existing maintenance program and staff, clogging would not be considered. In private development where maintenance may not be performed, the designer may add a factor of safety to the stormwater design to account for the anticipated level of clogging and accompanying reduction in the porosity of the pervious concrete pavement. Some specific case studies of field performance and clogging are provided in reports by Wanielista et al. (2005) and Delatte et al. (2007).

7.5.2 *Pervious area credit*—Many municipalities encourage green space and a reduction of runoff in development through restrictions on the amount of impervious area on the project site. Typically, impervious area is limited to 25 to 75% of a developed piece of property. Due to the nature of a pervious concrete pavement, it should not be considered impervious. With concerns over green space, however, it is rarely counted as pervious area. It is common, however, for municipalities to assign a pervious area credit for pervious concrete. Different municipalities have used values of 25, 50, or 100%, which to the owner means a reduction in required grassy or undeveloped area on the project site and an increase in the area that can be developed.

As an example, consider a project site that is 1 acre (43,560 ft^2 [4046 m^2]), with 10,000 ft^2 (930 m^2) of a pervious concrete parking lot. If the local municipality requires a 30% pervious area on the project site, then the site design would be limited to having 30,500 ft^2 (2800 m^2) of impervious area. This includes the building, sidewalks, and parking areas, and assumes no credit is given for the pervious concrete. With a 50% pervious area credit for the concrete parking lot, the developable area would be expanded to 35,500 ft^2 (3300 m^2)—a 16% increase in the amount of usable land on the site. This can make a project much more appealing to a developer, and with a reduction in undeveloped land, there can be a similar reduction in urban sprawl, as smaller sites could be used to fulfill specific development needs.

Local agencies are faced with the ever-growing regulations requiring stormwater treatment. It may be in their best interest to increase the percentage of credit given to pervious parking areas to the actual percent of runoff retained on-site to encourage more people to use the technology. Pervious concrete allows the city to grow with much less stress on storm drainage infrastructure. Because pervious concrete pavement allows water to flow back into dwindling aquifers, it offers a very rare opportunity to change stormwater from a liability into an asset.

CHAPTER 8—PERVIOUS PAVEMENT CONSTRUCTION

Construction of pervious concrete pavements should comply with project plans and specifications to provide a finished product that will meet the owner's needs and local regulations (ACI 522.1). Successful construction starts with thorough planning. A preconstruction conference, construction of test sections, or both, are recommended to address issues such as:

(a) Confirming that all project personnel are working from the latest set of plans and specifications, and all revisions are documented
(b) Verifying that all required documents and submittals have been completed
(c) Determining the construction sequence and joint spacing
(d) Arranging the staging area for equipment, material, jobsite trailers, personnel needs, and safety requirements
(e) Arranging adequate access for concrete delivery trucks and concrete conveying systems
(f) Selecting the optimum equipment for project size and anticipated conditions
(g) Coordinating on-site inspections, materials testing, or both. Inspectors and testing personnel should be included in conferences, test panel placement, and testing
(h) Verifying the proposed mixture design, material and admixture availability, and proposed delivery schedule with the concrete supplier
(i) Verifying that the pervious concrete contractor, concrete plant personnel, and testing personnel (Section 9.3) are adequately qualified
(j) Coordinating the test panel placement
(k) Confirming site work requirements
(l) Coordinate responsibilities with respect to curing and protection

8.1—General construction principles

The characteristics of pervious concrete dictate a construction process notably different from that for normal cast-in-place concrete (Offenberg 2005). The construction process is completed in the following general sequence: the pervious concrete is deposited, screeded, compacted, and jointed, and then is immediately cured with an approved spray-on curing compound and plastic sheeting, or just plastic sheeting. Equipment that has been used successfully to place pervious concrete includes both single-, double-, and triple-tube counter rotating roller-screeds; plate compactors; slipforms; laser screeds; high-density asphalt pavers; and machines specifically made or modified for placing pervious concrete. Finishing procedures should be employed that do not seal the surface. The amount and consistency of the cementitious material materials in the mixture will dictate which finishing procedures are appropriate to ensure a durable yet permeable surface. The amount of time needed to finish the pervious concrete is significantly different than for conventional concrete because there is no delay between placing and finishing required to allow evaporation of bleed water.

No matter what equipment is used, a pervious pavement cannot be successfully constructed unless the concrete placed has the correct consistency. If the pervious concrete is too dry, there will be issues with cohesiveness and with low cement hydration. Problems observed for mixtures that are too wet result either in sealing the surface voids or the paste fraction drains down, leaving a weak structure, and possibly clogging the pavement bottom. Admixtures and techniques, including hydration stabilizers, viscosity modifiers, water reducers, and internal curing, are helpful in producing and maintaining the proper consistency of pervious concrete. The low water content and porous structure, which exposes paste surfaces to evaporation, requires that delivery and placement be completed rapidly so that the sheet membrane curing can be in place quickly. The allowable time the fresh concrete can be exposed may be significantly reduced depending on environmental conditions, such as the potential for rapid evaporation. The porous structure also makes pervious concrete more sensitive to low temperatures during and after placement, thus dictating heightened attention to cold weather concreting practice. Temperatures below 50°F (10°C) can extend the minimum hardening time before opening to traffic.

8.2—Subgrade/subbase preparation

The subgrade is the bed on which the pavement structure is constructed and can be either native materials or imported fill. In some cases, pavement will be placed on a subbase of clean gravel or crushed stone, which may be used as a stormwater storage basin. If the compacted site soils or imported fill have sufficient percolation rates and the project is not located in an area where freezing and thawing is a concern, then the gravel subbase may not be required. The project engineer should make this determination based on local regulations, soil infiltration rate, stormwater volume, anticipated traffic loads, and pavement purpose.

When the subgrade soil properties require that a rock subbase be placed below the pavement as a stormwater storage basin, either a choker course or nonwoven, geotextile/filter fabric may be placed between the layer of rock and prepared subgrade. Geotextile allows water to pass through but keeps the soil in the subgrade from intermingling with the voids of the subbase layer. However, there are concerns in areas with heavy sediment loads that the fabric can clog over time and prevent water from migrating into the subgrade.

Well-prepared, uniformly compacted subgrade and subbase at the correct elevations are essential to the construction of quality pavement. The subgrade and subbase should not be muddy, saturated, or frozen when placement begins. In addition, the subgrade and subbase should be moistened before concrete placement begins. Watering the base in hot weather helps reduce its temperature and reduces the chance of accelerated hydration that can result in a reduction in pavement strength and could lead to premature pavement failure. To provide a level surface for pavement construc-

tion, wheel ruts should be raked out before concrete placement begins.

8.3—Placing

A well-planned construction layout can expedite construction operations, permit efficient use of placement equipment, and provide access for concrete delivery trucks. The contractor and designer should agree on joint layout and construction methods before construction begins. A drawing showing the location of all joints and the placement sequence should be available for reference. Locations of fixed objects should be established with the joint pattern and construction methods in mind. The approved jointing pattern should be marked on the forms or base as shown in the jointing plan prior to placement.

Pervious concrete placement should be completed as quickly as possible. Pervious concrete has almost no excess water in the mixture and is ready to finish as soon as it is placed on the ground. Fresh material exposed to the elements may quickly lose water that is needed for hydration. This fast drying of cement paste can lead to loss of strength and future raveling of the pavement surface. All placement operations and equipment should be designed and selected with this in mind. Equipment should be scheduled for rapid placement and curing of the pavement. Unless otherwise specified, begin curing within 10 minutes of concrete discharge, unless other steps are taken to extend placement and finishing time. In particularly hot or dry climates, these requirements may be reduced to curing within 10 minutes of discharge or 10 ft (3 m) after screeding operations.

8.3.1 *Forms*—Typical pervious pavement construction requires the use of edge forms, as is also typical for conventional cast-in-place slab-on-ground construction. Forms may be made of wood, plastic, or steel. The top of the form should be at the top of concrete elevation. Forms should be of sufficient strength and stability to support equipment used for screeding and compacting during placement. The subgrade and subbase material under the forms should be compacted in accordance with the designer's specifications. The length of the form pins should be selected based on the type of subgrade or subbase material. Enough form pins or stakes should be used to resist movement and bending. Kicker stakes may be required to prevent deformation of the formwork during edge compaction. When roller screeds or other compaction equipment will be overlapping the forms, it is important to remember that stakes and form securing materials be kept below the top of the forms to avoid impacting finishing and compaction operations. All forms should be cleaned and coated with the appropriate release agent as necessary.

8.3.2 *Depositing concrete*—Concrete should be deposited as close to its final position as practical. This is commonly accomplished by direct discharge from the chute of the mixer truck directly onto the subgrade or subbase (Fig. 8.3.2a). Generally, only one section of chute can be added to the fold down/flop chute section-mounted on the mixer truck, limiting the width of placement lanes to 15 ft (4.5 m). Some suppliers offer half-chute sections to extend the range. For placements that mixers cannot reach, or where the soil disturbance is to be minimized, a conveyor belt or other means of conveyance may be used (Fig. 8.3.2b). Care should be taken to inspect the mixture after conveying because some paste may be lost when using a belt placer. If not periodically cleaned, the excess paste can drop onto the fresh surface, clogging the pores. After the concrete is deposited, edge compaction should be completed in layers to the top of the final grade prior to strikeoff. The mixture should be deposited and cut to a rough elevation slightly above grade with a concrete rake or similar hand tool (Fig. 8.3.2c). Care should be taken to maintain the void structure. Over-vibrating and applying water to the pavement surface can cause surface sealing and is not recommended. Workers should minimize walking in the plastic concrete to prevent areas of differential concrete compaction and contamination with deleterious material.

Fig. 8.3.2a—Placement of pervious concrete by rear-discharge concrete truck (photo courtesy of S. Erickson).

Fig. 8.3.2b—Use of conveyor to place pervious concrete.

8.3.3 *Riser strips*—If additional compaction is desired, riser strips may be placed on top of the forms to provide an initial strikeoff elevation. These strips vary from 1/4 to 3/4 in. (6 to 19 mm) thickness; the necessary thickness will depend on the required surface compaction, thickness of the pavement section, the aggregate used in the pervious

Fig. 8.3.2c—Raking pervious concrete to rough elevation (photo courtesy of J. Kevern).

Fig. 8.3.4—Finishing pervious concrete using a cross roller (photo courtesy of B. Banka).

concrete, and the contractor's placement methods. Refer to Section 8.4 for more details.

8.3.4 *Placing equipment*—Placement methods vary depending on the project size, desired surface texture, and mixture workability. For small jobs such as driveways or for tight areas, a handheld straightedge or roller screed is acceptable. For larger jobs, roller screeds are common (Fig. 8.3.2c). When a straightedge or truss screed is used, a static roller is required for compaction unless otherwise allowed by the mixture specification. Weighted spinning-tube screeds (roller screeds) that maintain a head of material in front of the screed offer initial compaction and therefore may not require the same thickness (if any) for the riser and may eliminate the need for additional compaction with a static roller. If a roller screed is used, additional finishing is commonly completed with an adequate cross rolling tool (Fig. 8.3.4). The head of material in front of the rotating screed is critical to provide enough compaction to reduce riser strip thickness or to discontinue use of the static roller. When using this process, the mixture should be properly proportioned with a relatively fluid consistency to achieve adequate compaction.

Laser screeds, asphalt pavers, and concrete slipform equipment have been used for placing large volumes of pervious concrete in pavements. This process requires specialized expertise and experience in mixture proportioning and placement techniques. The key is that proper mixture consistency should be verified for the selected method.

8.3.5 *Miscellaneous tools*—Traditional concrete finishing tools such as edgers and come-alongs (a tool that looks like a hoe and has a long straight-edged blade) may be used to facilitate proper placement of pervious concrete. Bull floats and traditional concrete trowels should not be used unless the installer can demonstrate the ability to finish the mixture without sealing the surface or damaging the cement bond between aggregates. All finishing operations should be completed quickly and before the mixture begins to lose its sheen and starts setting. Manipulating a mixture after the initial set has begun will damage the bond between the cement and the aggregate and may result in surface raveling. After finishing and primary compaction has been completed, a secondary cross roller is often used to improve surface smoothness by reducing transverse waves caused from forward movement of the roller screed. The cross-roller is relatively light and used perpendicular to placement, similar to bull floating in conventional concrete. The cross roller does not provide any significant compaction but serves to reduce transverse high points created during screeding. Cross rolling on top of the plastic helps seat the plastic to the fresh concrete and prevents concrete from sticking to the roller (Fig. 8.3.4). However, this practice can prevent the craftsman from clearly identifying pavement surface defects that could be corrected by additional cross rolling.

8.3.6 *Using pavement as a form*—Special care should be taken when placing a pervious concrete section next to an existing placement, especially from the previous day (same-day, side-by-side placements, using mechanical equipment is not recommended). The following is the recommended procedure:

1. Carefully peel back the curing sheet that is covering the existing placement to expose the edge of the pavement. Care should be taken to keep as much of the previous placement covered as possible. Wet the uncovered area with water. Wetting is recommended to replace moisture loss caused by removing the plastic and reduces the chance of the fresh mixture losing moisture when it contacts the warm or dry existing placement edge.
2. Place a riser-strip or protective sheet on top of the finished placement and along the edge.
3. Place fresh pervious concrete up to the edge of the existing pavement and compact the fresh mixture to a level above the finished grade so the screed will strike the fresh mixture off to finished grade.
4. Using sheet metal or other thin-gauge material to protect the adjoining pavement, strike off the freshly placed pervious concrete to the proper elevation, being careful not to impact the existing placement.
5. Continue with roller compaction and finish as usual, making sure to align joints with previous placement.

6. Cover any exposed surfaces of the existing placement and cover the new placement with curing sheeting.

8.4—Compaction and finishing

The goal when finishing pervious concrete is providing compaction/densification of the mixture while maintaining an adequate void system. The compaction of the pervious surface creates a stronger bond between the aggregates and reduces the size of surface voids. This helps capture sediment particles close to the surface where they can be removed easier than if lodged deeper in the pavement. Edges are particularly vulnerable and should be compacted prior to screeding. One method of edge densification is to have a worker walk on the fresh pervious concrete along the edge to compact by stepping on the mixture (with a clean boot) parallel to the form. By applying their weight to the mixture, sufficient compaction will occur. This process may need to be repeated to ensure the compacted edge is left slightly higher than finished grade so the screed will cut the compacted edge to final grade. Other methods to compact the edge include the use of a tool such as a tamper or rake.

8.4.1 *Roller screed*—The most common pervious concrete compaction and finishing method uses a hydraulic, electric, or gas-powered roller screed to perform both the strike-off and compaction (Fig. 8.3.2c). The hollow tube is typically filled with water or sand to increase the screed weight for compacting the fresh concrete. A head of fresh concrete is maintained in front of the roller to ensure consistent density and surface texture.

Fig. 8.4.2a—Example of using a weighted fresno to correct cross roller marks.

Fig. 8.4.2b—Edging pervious concrete (photo courtesy of M. Offenberg).

8.4.2 *Post-compaction finishing*—Some situations require extra effort to ensure a quality pavement. Where ride quality is of special concern, as in drive lanes, the pavement may require the use of pervious mixtures that allow the installer to use finishing tools that allow a smoother finish than is possible with a cross roller alone. Weighted fresnos, spinning pan floats, or other wide tools capable of smoothing out vertical deviations should be allowed as long as the tool does not result in a sealed surface (Fig. 8.4.2a). All edges should be tooled, even against curbs, to reduce raveling because the curb and pavement will move independently (Fig. 8.4.2b). Care should be taken to make sure that proper compaction, finishing, and edging take place within minutes of placement. After strikeoff, compaction, and edging, any finishing operations that must take place should start without delay.

8.5—Jointing

Contraction joints, sometimes referred to as control joints, should be installed as indicated by the plans. They should have a depth of one-third to one-fourth of the thickness of the pavement. Joints may be installed in the fresh concrete with special tools or conventional saw cutting after the concrete hardens. Shrinkage cracks will occur in pervious concrete as well as in conventional concrete and can occur in large placements even before the concrete has had time to cure enough for saw cutting. Conventional concrete jointing tools may be used for small placements such as sidewalks.

If the contraction joints are saw-cut, the procedure should begin as soon as the pavement has hardened sufficiently to prevent damage to the surface. Only the minimum amount of polyethylene cover material should be removed that is required to saw cut the pavement. After sawing, the exposed areas should be flushed with water to clean the fines generated by sawing and ensure that sufficient water is present for proper curing. Immediately recover the exposed area with the polyethylene covering sheet as soon as saw cuts have been completed.

8.6—Curing and protection

The open pore structure of pervious concrete makes curing particularly important because of the larger paste surface area exposed to drying. Strikeoff, compaction, and curing operations should be kept as close together as possible to prevent the top surface of the pervious concrete from drying. Immediate curing of pervious concrete is vital for performance. Under favorable conditions of high humidity and low wind velocity, the cover material should be placed no later than 20 minutes following discharge. Under more severe environmental conditions, the cover material should be placed sooner.

There are currently two methods of curing pervious concrete using polyethylene sheeting. The first method is to use a thin painters poly, which is 33 mil, that, when stapled to

the forms and pulled snug, will allow for a shrink wrapping of the poly and keep the concrete from sticking to the roller when cross rolling is performed. The thin plastic sheeting is placed prior to being covered for the required curing period with a heavier poly sheeting that will greatly reduce any marks left on the concrete once the curing material is removed. A second method is to cross roll directly on top of the heavy plastic sheeting, which keeps the roller clean and acts as the curing material for the required curing period but is prone to leaving lines in the concrete from the moisture that rises through the concrete and is then deposited on top of the pervious concrete. These marks are only aesthetic blemishes that do not harm the durability of the pervious concrete. The cover material should be heavy-duty polyethylene sheet, meeting the requirements of ASTM C171, and of sufficient dimension to cover the entire width of pavement (Fig. 8.6a). Woven materials such as burlap and geotextile fabric should not be used, as they cannot maintain sufficient moisture in the concrete. For most pervious concrete mixtures, spray-applied curing compounds alone do not produce acceptable results. When adverse ambient weather conditions exist, such as high temperature, high wind, or low humidity, an evaporation reducer may be lightly sprayed on the surface before covering with plastic sheeting.

Fig. 8.6a—Demonstration of curing with plastic sheeting immediately after compaction (photo courtesy of C. Martin).

Fig. 8.6b—Example of use of sandbags to hold down curing material (photo courtesy of J. Kevern).

The polyethylene cover should completely cover all exposed concrete surfaces and should be secured in place outside of all pavement edges to prevent evaporation from the concrete and to also prevent being displaced by wind. Individual sheets should have sufficient overlap to provide an adequate seal. Reinforcing bars, lumber, sandbags, or concrete blocks may be used to secure the polyethylene cover to prevent it from being blown off (Fig. 8.6b). Fine materials such as soil or sand should not be placed on top of the polyethylene cover, as they may wash into the pores of the concrete during a heavy rainfall, or during removal of the cover. If wooden forms are used, the riser strips may be used to secure the sheets in place. The sheets should first be attached to the top of the form on one side of the lane by reattaching the riser strips to the top of forms with button-cap nails, with the polyethylene sheet sandwiched between the form and riser strip. The sheet should then be pulled as tight as possible to eliminate creases and minimize the possibility of discoloration or striping of the concrete. All surfaces of the pavement should be covered properly. Not doing so may result in raveling of the exposed areas. Any loss of moisture, such as from wind getting under secured plastic, can be detrimental to the proper curing and strength development of the pavement.

The owner should be made aware of possible discoloration of the pavement surface due to the differential curing under the plastic sheeting. Discoloring occurs when surface tension causes high-pH water to accumulate against the plastic sheeting. When the water evaporates, surface efflorescence remains. Over time, the discoloration should fade until the color is consistent. Discoloration may be removed with a light application of dilute muriatic acid. If muriatic acid is used to reduce surface discoloring, test the concentration and effectiveness in a noncritical area to verify that the selected concentration does not cause paste degradation or surface raveling.

For proper curing, the pavement should typically remain covered for at least 7 days for plain cement concrete mixtures, and 10 days for concrete mixtures that incorporate supplementary cementitious materials such as fly ash or slag. It may be necessary in cold weather to increase these typical curing times. Increased curing times under plastic do not

Fig. 8.6c—Painted lines visible on pervious concrete pavements (photo courtesy of M. Offenberg).

increase the strength significantly beyond 7 days; however, additional curing time does result in improved abrasion resistance (Kevern et al. 2009b). Paint striping should be applied only after the curing period has passed (Fig. 8.6c). No traffic should be allowed on the pavement during curing. The contractor should take measures to prevent damage to the pavement due to abuse from other construction operations. Specifically, one should prohibit premature removal of the curing material and prevent any traffic on the pervious concrete pavement. Additionally, the contractor should not allow storage of any materials on the pavement, other than those items that are used to hold down the plastic sheeting.

8.7—Cold weather protection

Pervious concrete is more sensitive to cold weather than conventional concrete (Section 8.1) and, therefore, pervious concrete construction may be suspended or curing blankets used when ambient temperature during, and 1 day after, placement is expected to fall below 40°F (4°C). Hydration stabilizing and retarding admixtures are common in pervious concrete mixtures to help extend workable life. Because of the set-delaying admixtures, less heat is generated or retained by pervious concrete to assist hydration. Also, because of the delayed set and rapid evaporation caused by the open pore structure and low *w/c*, hot water should be used with care when batching pervious concrete in cold weather. During curing, measures should be taken to protect the pervious concrete from freezing while maintaining moisture for the time necessary to achieve the desired strength. Curing blankets work sufficiently well to serve this purpose. If the pavement is installed in temperatures lower than 50°F (10°C), the contractor should protect the concrete from freezing and record the concrete temperature no less than twice per 24-hour period in accordance with ACI 306.1. Additionally, the contractor should submit detailed procedures for the production, transportation, placement, protection, curing, and temperature monitoring of the concrete.

8.8—Hot weather protection

In hot weather, transporting, placing, and compacting should be completed as quickly as possible. Mixtures containing admixtures, especially hydration stabilizer, will require more admixture in hotter or drier conditions. After consolidation and before placing the polyethylene sheeting, the surface may be misted with water or an evaporation retardant if the surface appears to be losing its sheen appearance. If weather conditions lower the working life of the mixture enough to prevent all installation procedures to take place before the mixture loses its metallic sheen, the placement should be suspended until ambient conditions improve. When hot weather is anticipated, the contractor should submit detailed procedures for the production, transportation, placement, protection, curing, and temperature monitoring of the pervious concrete.

CHAPTER 9—QUALITY CONTROL AND ASSURANCE INSPECTION AND TESTING

9.1—General

As with any engineered material, it is important to verify the quality of a pervious concrete pavement. Tests performed on the subgrade and subbase conditions are to ensure adequate density, support value, and permeability. Testing of the pervious concrete mixture should be conducted for the fresh and hardened properties of the concrete for quality assurance of adequate density and thickness. As with all concrete, cooperation and good communication between the producer, contractor, and testing agency are important to ensure proper testing and allow for a high-quality final product.

ASTM Subcommittee C09.49 developed three test methods specifically for pervious concrete (C1688/C1688M, C1701/C1701M, and C1747/C1747M), allowing for standard measurement of the fresh and hardened density and void content, the infiltration, and the raveling potential of the mixture. Many of the present ASTM and AASHTO testing methods are applicable to a pervious concrete pavement installation. Due to the physical characteristics of the material, however, not all traditional concrete tests are appropriate for pervious concrete.

Quality control for pervious concrete can be divided into preconstruction mixture development and site qualification, production testing, and inspection of the fresh concrete material, including test panels where testing targets are established, and post-construction qualification and testing of the completed pervious concrete system. These three categories are further delineated in the following.

9.2—Preconstruction inspection and testing

As with other paving materials, preconstruction testing should be used as the primary means for mixture development. Pervious concrete producers should establish reliable data and history for their pervious concrete mixtures. There are several tools that can be used by producers for mixture development and evaluation. As mentioned in Chapter 4, ASTM C29/C29M can be used to determine the dry rodded unit weight and void in the coarse aggregate. ASTM D1747 is especially useful for mixture development. It can be used to compare several potential mixtures with the goal of producing the most durable pavement. ASTM C1688/C1688M may be used to generate a fresh void-density relationship for the pervious concrete mixture being developed. A detailed study of procedures can be found in Kevern et al. (2009d). A similar procedure can be used with 4 in. (100 mm) specimens and ASTM C1754/C1754M to develop a relationship between fresh density per ASTM C1688/C1688M, hardened density, and void content for the specific pervious concrete mixture combination.

Preconstruction inspection of the site should also be performed. Determining the permeability of the base and subgrade soil is particularly important in the design and construction of the pervious concrete system. Basic tests of the properties of the subgrade should include a particle size analysis (ASTM D422), classification (ASTM D2487;

ASTM D2488), and standard or modified proctor test (ASTM D698; ASTM D1557) or maximum/minimum index density (ASTM D4253; ASTM D4254) for noncohesive soils. The results of these tests will provide the designer with the input data for the pavement design.

The standard percolation test used for designing septic fields is not an appropriate test for determining subgrade permeability for pervious pavements, but a double-ring infiltrometer (ASTM D3385) or other suitable test should be performed to adequately test the permeability. For small projects, these tests may not be necessary, especially if the designer has previous experience with similar soils.

Normal soil testing procedures for subgrade density (compaction) in accordance with a standard test procedure should be performed before concrete placement as part of a normal quality-control plan. Where subgrade materials are cohesive in nature, inspections should verify that they have not been sealed off prior to placement of the subbase aggregate. It should be noted that subbase materials are often gap-graded and are not moisture-sensitive. For these materials, relative density should be specified rather than using a proctor-determined maximum dry density.

Often, subgrade and subbase materials are placed and inspected early in the construction schedule but are clogged or otherwise impacted by construction operations that take place prior to pervious concrete placement. The subgrade and base materials should be protected prior to the placement of pervious concrete to ensure functionality of the entire pervious concrete system.

Delay excavation of pervious pavement areas to protect the subgrade. Historically, site excavation occurs early, and the unpaved parking areas are used for staging during construction. This practice can lead to over-compaction of the subgrade by construction traffic and often leads to the need to remove additional subgrade before paving and usually results in additional costs. Instead of excavating the parking areas early, when possible, require the construction traffic to operate elsewhere or minimize initial site grading where construction traffic is unavoidable. Excavate pervious areas only when ready to complete the paving work

9.3—Inspection and testing during construction

Included in this phase of the pervious concrete placement process is the placement of test panels, as specified in ACI 522.1. The test panels should be used to establish all critical testing targets for the production placement. As such, it is important that all mixture variables be kept as close as possible to anticipated production values to minimize differences between the test panels and the production placement. The test panels are used to validate the mixture design data provided by the concrete producer and confirm the pervious concrete contractor's ability to properly place the pervious mixture under anticipated project conditions. It is important that realistic pervious concrete fresh density (per ASTM C1688/C1688M) be established for proper evaluation of the mixture during placement operations. Contractor performance can be confirmed visually as well as with ASTM test methods for hardened pervious concrete. These include ASTM C1701/C1701M and ASTM C1754/C1754M. Research has shown that ASTM C1754/C1754M test results will be approximately 4 to 8 lb/ft^3 (64 to 128 kg/m^3) less than the related ASTM C1688/C1688M results, but this relationship is dependent on the concrete mixture design and the contractor's placement operations, and these should be established during the test panel evaluation.

The primary means for quality control of pervious concrete as delivered to the project should be ASTM C1688/C1688M using the target values established during the test panel placement. Density testing is recommended once per truck, although this frequency can be adjusted based upon the delivery frequency and testing budget for the project. While the current version of ACI 522.1 recommends ±5 lb/ft^3 (80 kg/m^3) for incoming fresh density, testing has shown that a tighter tolerance of ±3 lb/ft^3 (48 kg/m^3) is quite possible from a production standpoint and results in a more consistent in-place void content. For this reason, plant quality control during production is critical, and special attention should be paid to aggregate moisture during batching operations. Testing has shown that the fresh density of a single load of pervious concrete can vary by as much as 6 to 8 lb/ft^3 (96 to 128 kg/m^3) from the beginning to the end of the truck, so pervious concrete properties should be continuously monitored by the producer, the installer, and the construction inspector so that any necessary adjustments can be made as soon as possible. Many project specifications forbid the addition of water at the construction site to adjust standard concrete mixtures; however, for pervious concrete, repeated adjustments may be necessary and are critical to maintain mixture consistency and sufficient paste properties.

A useful tool for evaluating consistency and the potential for paste sealing is the inverted slump cone test. This test is performed by placing a slump cone, inverted, upon a level, nonabsorptive surface. The cone is filled to the top with pervious concrete with no consolidation performed. After 2 minutes, an observation is made of the bottom of the cone for a paste ring. If paste has drained through the concrete to leave a ring at the bottom of the cone, it indicates that the pervious concrete is too wet or has an unstable paste coating, and it is likely that the concrete will clog on the bottom and infiltration will be reduced. If there is no paste ring and the sample appears stable, further evaluation of the consistency can be performed by lifting the cone slowly. The concrete should slide from the cone with no more than several gentle vertical shakes. Failure to do so may indicate that the pervious concrete is too dry.

Field tests and inspections of pervious concrete should be performed by an individual certified as both an NRMCA Certified Pervious Concrete Technician or equivalent and an ACI Concrete Field Testing Technician—Grade I or equivalent.

9.4—Postconstruction inspection and testing

For quality assurance purposes, three cores of the pavement for thickness and density should be tested for each 5000 ft^2 (465 m^2) of pavement placed. Core samples should be obtained in accordance with ASTM C42/C42M not

less than 7 days after placement and be 4 in. (100 mm) in diameter. The cores should be measured for thickness by an ACI Certified Laboratory Technician II according to ASTM C174/C174M and tested for density according to ASTM C1754/C1754M. The placement thickness should be determined using untrimmed, hardened core samples. After thickness determination, the cores should be trimmed and measured for unit weight by the same method used for the testing of the test panels. The acceptable hardened density should be within ±5% of the approved hardened density from the test panels. It should be noted that the fresh density found using ASTM C1688/C1688M will not be comparable to the hardened density found using ASTM C1754/C1754M.

ASTM C1701/C1701M is the standard method to be used to confirm the pavement meets or exceeds 250 in./h (6350 mm/h) of drainage. Due to the local variability of pervious pavements, multiple tests should be performed, and the pavement evaluated as a whole or in sections or lots rather than as individual test locations. Whether or not ASTM C1701/C1701M infiltration testing is performed as part of the project quality control/quality assurance, it is recommended that the contractor perform ASTM C1701/C1701M testing when curing is completed for each pavement section. This establishes a baseline infiltration rate for future monitoring and maintenance purposes.

In addition, visual inspection of the cores allows for verification of the necessary open void space to facilitate drainage. Visual inspection that shows a fully closed or severely restricted pore structure may indicate a pavement that will not function properly, and sections demonstrated to be essentially impervious should be removed and replaced. Localized areas of impervious pavement may be acceptable considering the overall average infiltration of the pavement. Agreement as to what is deemed impervious, and the method of measurement, should be achieved before initial placement and validated on the test panel.

At no time should acceptance be based on the compressive strength of the pervious concrete, either as delivered or as cored from the pavement. Because increasing compaction can increase the pervious concrete compressive strength, there is a wide range of strengths that can be generated from a single delivery of pervious concrete. Studies are underway to develop a standard method for testing the compressive strength of pervious concrete. Typical coring procedures, when used on pervious concrete, disturb the cement paste matrix such that compressive strength results may be inaccurately low. Local experience through completed projects, test panels, or both, should give an indication as to whether a specific mixture proportion and material combination will have sufficient strength to withstand the stresses of the design traffic loads.

CHAPTER 10—PERFORMANCE

10.1—General

Pervious concrete pavements have been in service for more than 30 years, which has allowed time for comprehensive research studies and standards to be developed to better understand performance. Information from controlled studies is available concerning the long-term performance of pervious concrete pavements. The performance parameters discussed in this chapter include changes in infiltration rates, structural distress, surface distress, resistance to freezing and thawing, resistance to deicers, and overlay performance.

10.2—Changes in infiltration rates

In the past, maintenance had been a regulatory concern that prevented wide acceptance of pervious concrete. A pervious concrete pavement today will still maintain permeability even when clogged. Clogged pores or subgrade prevent stormwater from percolating through the concrete at high rates (Wanielista et al. 2007; Mata and Leming 2008). Thus, if stormwater is unable to drain through the pervious concrete layer at the design rate, it is no longer sufficiently pervious, the design benefit assumption is no longer valid, and the pavement has failed. Pervious concrete pavements can perform well for years with some level of clogging (Wanielista et al. 2007), but the rate should be above the design rate. Clogging occurs when foreign material fills in the open pore structure, usually on the top surface, and as a result restricts the ability of water to flow through the pervious concrete pavements. These materials can be fines that enter the pervious concrete matrix or vegetative matter that collects on the surface or in the pores of the pervious concrete. Fines can be water-borne, wind-borne, or deposited onto the pervious concrete pavement by traffic. Vegetative matter comes from trees or plants adjacent to the pervious concrete pavement. Waterborne fines come from stormwater runoff that originates outside the limits of the pervious concrete pavement and transports material onto the pavement. Clogging, leading to potential problems in serviceability, has been regarded as one of the primary drawbacks of all permeable pavement systems. A good site design of the pervious concrete pavement that prevents stormwater or traffic from introducing fines onto the pavement will minimize clogging. For example, pervious concrete pavements should be placed at elevations above adjacent landscaping, with the landscaping sloping away from the pavement. Wind-borne fines are generally of limited volume in many areas but could be of concern in arid areas. Vegetative matter will routinely be deposited onto the surface of pervious concrete pavements, requiring periodic cleaning. Construction operations adjacent to pervious concrete pavement may also cause fines to be deposited. Construction, therefore, should be sequenced to avoid deposition of these fines.

A field-performance investigation was conducted in Florida in 1989 on pervious concrete pavements up to 13 years old (Wingerter and Paine 1989). The study concluded that pervious concrete pavements that are properly designed, constructed, and maintained showed only minor clogging after many years of service. The study also included measurement of the percolation rate for clogged pervious concrete pavements. The percolation rate of the clogged pervious concrete pavement was equivalent to that of the adjacent grass. Another investigation (Wanielista et al. 2007) of several field sites in the southeastern United

States indicated that pervious concrete pavements that were installed 10 to 15 years prior, with no maintenance requirements, were operating as designed with virtually no clogging. That study also investigated various potential methods for rejuvenation (included pressure washing or vacuum sweeping of the pavement) of those pervious pavements where clogging had occurred (Wanielista et al. 2007). A more recent study (Schaefer et al. 2011) related to the problem of clogging was conducted using design porosities of 15, 20, and 25% and three sediments: sand, silty clay, and blended sand and silty clay. The fine-grained, silty clay had almost no effect on the ability of water to flow through specimens at typical stormwater concentrations. The results with sand and blended materials showed that clogging was only an issue at the lowest porosity and primarily for the blended materials. In most cases, sufficient permeability remained even after clogging had occurred and that water flow through the pervious concrete was not an operational issue for most pervious pavements. Several rehabilitation methods were also examined. Dry vacuuming was found to be the best method to rejuvenate a clogged pavement. Power washing was the best method followed by vacuuming for those pavements that were clogged with blended materials (Schaefer et al. 2011). Changes in infiltration rates can be monitored throughout the life of the pavement using ASTM C1701/C1701M. This field monitoring will establish a base infiltration rate from start of construction and allow for annual reporting of potential clogged areas within the pavement to be addressed by a maintenance program.

For a pervious pavement system to perform well, it may need to be maintained at some regular interval. If a pavement is in a harsh environment, such as a coastal area, or anywhere that would cause heavy accumulations of fines, it may be necessary to perform this preventive maintenance more frequently. A qualified professional such as a licensed professional engineer or landscape architect should inspect the pavement to determine an appropriate maintenance schedule, if it is functioning properly, or if cleaning is necessary.

10.3—Structural distress

Structural distress in pervious concrete pavements generally takes two forms: cracking or subsidence due to loss of subgrade support. Structural distress can be caused by heavy loads (beyond the structural capacity of the pavement), weak subgrade materials, or horizontal water flow through the pervious concrete paving that washes away subgrade material. High surface contact pressures or a weak pervious concrete surface results in the surface distress, raveling, which normally does not impact the structural capacity.

10.4—Surface distress

The most common surface distress is raveling. Raveling is most often caused by construction-related issues including poor or improper mixture design, inadequate compaction, and insufficient curing. Curing is especially important for pervious concrete because the high porosity and low *w/cm* allows rapid moisture loss from the fresh concrete due to evaporation. Additional studying of curing methods will be necessary for large-scale use of pervious concrete in roadway applications and as new products and techniques emerge (Kevern et al. 2009b). A field performance investigation carried out in Florida (Wingerter and Paine 1989) indicated that pervious concrete pavements with surface raveling were caused by an inadequate *w/cm*, inadequate compaction, or improper curing procedures. The investigators reported that the pervious concrete pavement projects had no signs of structural distress. Once a top layer of loose surface material has been removed, the raveling often stopped. ASTM C1747/C1747M is an abrasion test to assess a mixture's resistance to surface distress. Figure 10.4 illustrates the raveling phenomenon that does not indicate structural distress of the pavement. Kevern and Sparks (2013) discuss several techniques to remediate surface raveling. Sprayed-on surface-densifying agents, typically used on polished interior floors, significantly reduce raveling of poorly cured pervious concrete. When surface raveling is severe, a thin protective overlay or milling of the top surface are effective mitigation strategies (Kevern and Sparks 2013; Kevern et al. 2011).

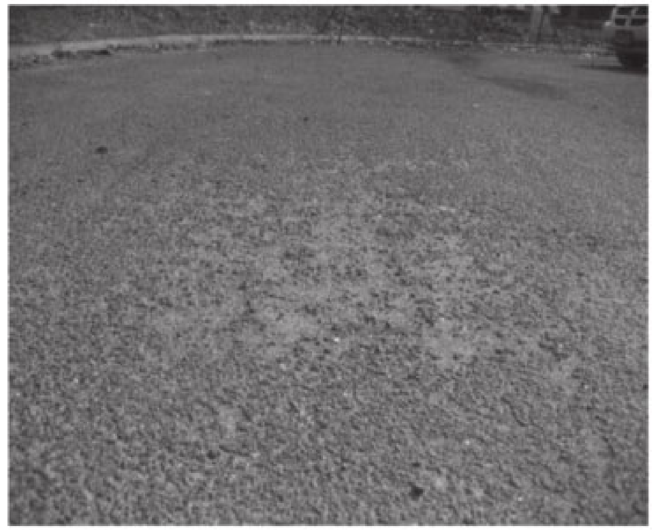

Fig. 10.4—Surface raveling distress of pervious concrete.

10.5—Resistance to freezing and thawing

The void structure of pervious concrete is not the same as the entrained air in regular portland-cement concrete. In properly designed and installed pervious concrete pavements, water drains through to an underlying drainage layer and soil and will not be retained in the void structure. When the pervious concrete is completely saturated and subjected to freezing, however, the water has no place to drain. This can result in excessive stresses on the thin cement paste coating the aggregates and may cause deterioration of pervious concrete installations. Some fully saturated non-air-entrained pervious concrete had poor freezing-and-thawing resistance when tested in the laboratory according to Procedure A of ASTM C666/C666M (Neithalath et al. 2005b). It is possible to add air-entraining admixture to pervious concrete mixtures to protect the coating paste, but the entrainment of

air cannot be easily verified or quantified by current standard test methods (Kevern et al. 2008b, 2009e). The National Concrete Pavement Technology Center (Schaefer et al. 2006) tested several different mixture designs for resistance to freezing and thawing. They determined that saturated samples made according to one mixture design only had a 2% mass loss when subjected to 300 freezing-and-thawing cycles in accordance with ASTM C666/C666M, Method A. This mixture incorporated No. 4 aggregate, 7% sand, 571 lb/yd^3 (338 kg/m^3) of cement, and a 0.27 *w/cm*. This mixture used both air entrainment and high-range water-reducing admixtures. Samples made according to this mixture had a void content of 18.3%. The results indicated that the addition of binder latex to the mixture helped with resistance to freezing and thawing, but not to the same extent as adding a small amount of sand to the mixture. Pervious concrete that is partially saturated could possibly have sufficient voids for water movement, demonstrating good freezing-and-thawing resistance. ASTM C666/C666M Procedure A is used to test concrete samples saturated under atmospheric pressure. This fully saturated technique does not simulate the performance of pervious pavement in the field because properly built installations in freezing-and-thawing environments contain a mechanism for draining water out of the pavement. However, the degree of saturation in clogged specimens can cause critical saturation in the field and potentially exacerbate freezing-and-thawing deterioration (Guthrie et al. 2010). Currently, there is no standard method for evaluating the resistance to freezing and thawing of pervious concrete and, as a best practice, the most important factor for good durability is its ability to drain any water entering its structure in the anticipated weather conditions. These precautions are recommended to enhance the freezing-and-thawing resistance of pervious concrete:

(a) Use an 8 to 24 in. (200 to 600 mm) thick layer of clean aggregate base below the pervious concrete.

(b) Attempt to protect the paste by incorporating air-entraining admixtures in the pervious mixture. Limited and preliminary lab testing shows that fully saturated air-entrained pervious concrete had significantly better freezing-and-thawing resistance when tested under ASTM C666/C666M. Additional studies conducted show that the RapidAir test is an effective means of determining the entrained air void structure in pervious concrete (Kevern et al. 2008b). Air entrainment increased paste volume and improved the workability and durability of pervious concrete and is recommended to be used in pervious concrete mixtures (Schaefer et al. 2011).

(c) If the aggregate base is not thick enough to drain all of the water through the paving, then install a perforated polyvinyl chloride (PVC) pipe in the aggregate base and connect the pipe to a drain outlet. The drainpipe should be set at an elevation that prevents water from saturating the pervious pavement.

(d) Consider adding a small amount of sand to the concrete mixture. Results confirmed previously published reports that sand should be included in the mixture to be frost resistant when saturated or normally saturated, regardless of the addition of air-entraining admixture (Mata 2008; Kevern et al. 2008a).

The durability of pervious concrete under freezing-and-thawing conditions has been well documented, with no deterioration in the field specifically due to freezing-and-thawing cycling known to exist (Delatte et al. 2007). However, field experience now shows severe deterioration when deicing chemicals are applied too soon after installation, and with prolonged heavy use of deicing products.

Not every situation warrants using all these safeguards. The safeguards are organized in the order of preference. There are many pervious concrete projects in Georgia, Pennsylvania, Tennessee, North Carolina, and New Mexico that are subject to various freezing-and-thawing conditions that are performing admirably (NRMCA 2004, 2007). Baas (2006) surveyed individuals across the country and asked them to describe their observations of pervious concrete freezing-and-thawing resistance. Respondents in Ohio, Minnesota, Northern Kentucky, Tennessee, Indiana, and California did not report any freezing-and-thawing deterioration of pervious pavement installations. Pervious concrete installations in the heavy snow areas of Colorado, Utah, Vermont, New Hampshire, Nevada, Montana, and Northern Arizona have also shown no signs of deterioration due to freezing-and-thawing cycling. The same can be said for the Maritime Provinces of Eastern Canada, where numerous pervious concrete installations have also taken place and where air-entrained conventional concrete is typically specified. Field performance was investigated for approximately two dozen pervious concrete sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. Generally, the installations evaluated had performed well in freezing-and-thawing environments, with little maintenance required. They were, however, relatively new, so there is a need to follow up later on field performance (Delatte et al. 2007). Pervious concrete is historically not recommended in freezing-and-thawing environments where the groundwater table rises to a level less than 3 ft (0.9 m) from the top of the surface of the subgrade.

10.6—Resistance to deicers

In cold-weather regions, deicers are frequently applied to a conventional pavement surface to improve slip resistance. Due to extended field experience, deicers are well known to damage pervious concrete.

Water freezes within the pervious concrete, but there can be water (ice or snow melt) on the surface. If there are deicers in that water and it refreezes, that can damage the surface, typically exhibited as raveling. One way to avoid this condition is through regular surface cleaning, which decreases the risk of standing water with deicers that freeze.

10.7—Repairing pervious concrete pavements

10.7.1 *Grinding/milling*—High spots can be ground with a weighted grinder; however, the grinder will cut through and expose the aggregate in ground areas, changing the appearance of the pavement. If insufficient curing of the pervious

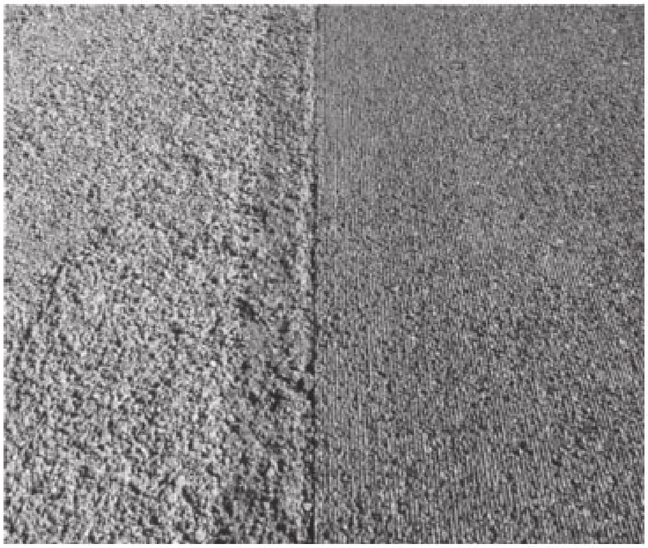

Fig. 10.7.1—Diamond grinding to remediate surface raveling.

concrete surface results in excessive raveling, milling off the weak surface into competent material is a remediation option (Fig. 10.7.1). Petrographic analysis on core samples should be performed first to determine the extent of drying and milling depth.

10.7.2 *Overlays*—When the surface drying extends beyond a depth suitable for milling, a thin overlay (2 in. [50 mm]) may be a more suitable option than a complete removal and replacement (Kevern and Sparks 2013). For a pervious concrete on pervious concrete overlay to be successful, any underlying loose material should first be removed, and the site should be able to accommodate the change in grade. The key for success of a pervious overlay is to ensure good bonding with the underlying material. The overlay mixture should be sufficiently workable to allow paste to attach to the existing material. The existing pervious concrete should be moistened just prior to placement to help increase the bond strength.

10.7.3 *Holes or low spots*—Small holes (low spots) should be patched with an aggregate/epoxy blend or latex-modified cement. To match the appearance of the pavement surface, the aggregate may be coated with wet cement and cured before patching. Large holes should be patched with pervious concrete of the same mixture proportions as the original surface. When patching, it is highly unlikely that the color of the patch will match the original surface material. Epoxy bonding agents or latex-modified cement may be used to ensure proper bonding between the old and new surfaces. Acrylic paints have been used to disguise the area of the patch with varied success. Unbonded thin sections of patch material may not remain intact under traffic loading. If in doubt, a full-depth repair is recommended.

10.7.4 *Utility cuts*—In the event that a section of pervious concrete is cut, a full-depth repair should be performed. This would include removing a square section the width of a placed lane such that the new material would be large enough to maintain its structural integrity under loading.

Table 10.8—Typical maintenance activities for pervious concrete placement

Activity	Schedule
(a) Ensure that paving area is clean of debris (b) Ensure that the area is clean of sediments (c) Remove loose vegetation with leaf blower	Monthly
(a) Seed bare upland areas (b) Vacuum sweep to keep the surface free of sediment (c) Remove sediment buildup from upstream sediment traps, swales, or structures	As needed
(a) Inspect the surface for deterioration or spalling	Annually

10.8—Maintenance

Pervious concrete pavements are stormwater infiltration-based systems. While studies have shown that even heavily clogged pervious pavements will still effectively drain most storm events, all permeable pavements work best when kept clean. Ideally, the pavement will be designed to limit sediment exposure by isolating run-on from landscaped areas with a swale and draining other nonpervious pavements elsewhere. In all cases, early removal of vegetative and other sediment loads is the most effective way to maintain infiltration. Water passing through the pavement will carry varying degrees of soluble and insoluble pollutants. Most of this debris will be deposited on or near the pavement surface. Maintenance of pervious concrete pavements consists primarily of removing the accumulated debris. Use of a leaf blower during regularly scheduled landscape maintenance or regular vacuuming by pavement maintenance companies is recommended. If drainage falls below acceptable levels, as measured by ASTM C1701/C1701M, a deeper cleaning will be required. Pressure washing is effective, but care should be taken to carefully monitor the pressure. If damage is evident, reduce pressure or hold the nozzle farther from the surface. Pressure washers with rotating nozzle heads are especially effective. A small section of the pavement should be pressure washed using varying water pressures to determine the appropriate pressure for the given pavement. Power vacuuming removes contaminants and debris by extracting them from the pavement voids. The most effective scheme, however, is to combine the two techniques and power vacuum after pressure washing. A sample maintenance schedule is found in Table 10.8.

Research conducted by the Florida Concrete and Products Association (1990) quantifies the extent of contaminant infiltration in pervious concrete parking lot pavements. Five parking lots were examined as part of the study, and the level of contaminant infiltration was found to be quite low. Infiltration was found to be in the range of 0.16 to 3.4% of the total void volume after up to 8 years of service, and brooming the surface immediately restored over 50% of the permeability of a clogged pavement.

10.9—Pervious concrete overlay field durability and performance

A pervious concrete overlay was constructed on the MnROAD Low Volume Road, a cold region pavement test track near Albertville, MN, USA, in October 2008

Fig. 10.9—Placement of pervious concrete overlay for noise reduction and skid resistance.

over concrete originally placed in July 1993. The pervious concrete overlay was nominally 4 in. (100 mm) thick with formed joints approximately over the original skewed joints (Fig. 10.9). The original mixture design development work envisioned machine placement of the overlay. Because of weather delays and equipment availability, a powered roller-screed was used for placement. The construction methods used included roller screeding, jointing with a mechanical cutter, and curing under plastic for 7 days. The construction did leave some surface irregularities in the form of stretch markings and surface sealing. Condition surveys of the overlay were conducted in 2009, 2010, and 2011. The primary distress to the overlay pavement was joint deterioration. With a minor amount of cracking, the joint deterioration is believed to be the result of the method of joint placement; saw cutting the joints would have resulted in less deterioration. The joint deterioration increased each year and is likely due to snowplow effects. The flow characteristics have been measured each year, with high infiltration results and consistent flow from year to year. Operations during rain events indicate that the pervious overlay quickly removes rainwater from the pavement surface and that the water migrated laterally to the side of the pavement, indicating pervious concrete is a successful tool for mitigating splash and spray as well as reducing hydroplaning (Schaefer et al. 2011). In addition, noise measurements have been conducted on the overlay at the MnROAD Low Volume Road and reveal a remarkably quiet pavement. While traditional concrete noise levels range from around 100 to 110 decibels adjusted (dBA), values for the pervious concrete in 2009 and 2010 range between 96 and 98, making the pervious overlay one of the quietest concrete pavements in place.

CHAPTER 11—LIMITATIONS, POTENTIAL APPLICATIONS, AND RESEARCH NEEDS

The most widespread applications of pervious concrete include paving and surface treatments to permit drainage. These can take many forms, such as parking lot surfaces, roads, storage, and liquid/solid separation operations such as in agricultural manure dewatering. Each use has different limitations and concerns. Further research would help to extend its use in these and in other applications and to verify its performance in various environments.

Some areas of research needs are as follows:

(a) Strength determination and limitations
(b) Characterization of material structure
(c) Freezing-and-thawing and cold climate applications
(d) Porous grout and other pore pressure reduction potentials
(e) Stormwater management
(f) Environmental filtering/remediation potential
(g) Surface deterioration and repair
(h) Development and standardization of broader testing methods
(i) Nondestructive test methods for performance evaluation and prediction
(j) Urban heat island effect, carbonation, and other thermal properties
(k) Other novel applications

11.1—Pervious concrete in cold climates

More research would be valuable to evaluate the ability of known technologies in protecting pervious concrete in cold climates. Although there have been many pervious concrete pavements installed in colder areas, several questions remain to ensure pervious concrete can be used with greater confidence and for broader application in cold climates. There are two main issues that should be further addressed: the first is the impact of freezing and thawing on the concrete in a broader range of applications, and the second is to establish with greater certainty the potential impact of deicers on the concrete, particularly because the open pore structure allows for faster infiltration of these salts into the concrete matrix than in traditional concrete pavement. The first known direct observation of pervious concrete's behavior on freezing was a laboratory experiment by the U.S. Army's Cold Regions Research and Engineering Laboratory (Korhonen and Bayer 1989). Samples of pervious concrete without air entrainment, reinforcement, or other treatment for frost damage protection were repeatedly frozen and thawed. At intervals during the testing sequence, samples were removed from the freezing cycle and put under compressive force to test their loss of breaking strength. Those that had been frozen in dry or damp (wetted, then drained) conditions showed little loss of strength over 160 freezing-and-thawing cycles. A later laboratory test (Yang and Jiang 2003) showed that after 25 cycles of freezing and thawing in air, the unconfined compressive strength of five samples decreased 15 to 23%. Similar samples that had been frozen in water-filled containers, however, progressively deteriorated. Assuring rapid drainage of a pervious slab into a well-drained base reservoir, however, is a critical preventive measure against the effects of freezing. In cold regions, air-entraining agents are routinely added to concrete to protect it from frost damage (AASHTO 1993). Experience primarily from building construction suggests that air entrainment improves

the resistance of pervious concrete to damage from freezing-and-thawing cycles as it does for dense concrete (Florida Concrete and Products Association 1990; Monahan 1981; Neithalath et al. 2003). Liquid polymer and latex additives may help by sealing the cement binder's micropores and preventing the entry of water. Supplementary cementitious materials, various fibers, and liquid polymers can enhance concrete's strength, limit shrinkage, and thereby improve its resistance to freezing-and-thawing conditions and deicing chemicals (Pindado et al. 1999).

While air entrainment has been shown beneficial and necessary for freezing-and-thawing resistance of pervious concrete produced in laboratory conditions, there are not any corresponding field-scale testing sections (Kevern et al. 2008b, 2009e). Entrained air has been successfully measured on hardened specimens using automated analysis correlated to ASTM C457/C457M, which matched laboratory freezing-and-thawing performance (Kevern et al. 2008b). Fresh air void analysis in the field has been shown problematic with conventional pressure or volume techniques, with the air void analyzer (AVA) showing promise. However, research is needed to evaluate a range of entrained air contents in the field and determine what level is sufficient for good durability in a variety of conditions. Of even more importance may be the observed lack of air entrainment in certain field placements, which showed good performance in the laboratory (Kevern et al. 2009e).

Field performance has shown severe damage to pervious pavements caused by deicing chemicals if treated too soon after placement and in regions where deicing is used heavily.

11.2—Characterization of the material structure

The properties and performance of any porous material depend extensively on pore structure features such as the total pore volume, pore sizes and their distribution, and the connectivity and tortuosity of the pore structure. Because pervious concrete is primarily used for stormwater management, the functional performance characteristic that is more often a concern for the end user is the permeability. Porosity is considered as the most important feature of the pore structure of porous materials, but it alone is insufficient in providing a complete description of the material performance. A higher porosity does not necessarily ensure higher permeability because the permeability is a function of the pore surface area, pore sizes, and tortuosity. Using aggregates of different sizes in pervious concrete to produce the same porosity has resulted in different permeability values (Neithalath et al. 2006). A proper understanding of the pore structure feature and how it is influenced by the material parameters and mixture proportioning needs careful and thorough investigation. A few studies have reported the influence of aggregate gradation and blending on the porosity, pore sizes, and connectivity of pervious concretes (Neithalath 2004; Neithalath et al. 2006; Low et al. 2008) using mathematical and statistical procedures. To develop performance-based material design for pervious concretes, significant research is needed in understanding the pore structure of this material. The macroporosity of pervious concretes can often lead to crack arrest effects if the porosity and pore sizes are conducive. This influences the structural performance of the material. A comprehensive understanding of material performance and a material design-based mixture proportioning, therefore, can be accomplished only if the pore structure characteristics are well understood.

11.3—Strength and other testing needs and limitations

The current established testing methods for concrete are in many cases not applicable to pervious concrete. Either new or modified testing methods need to be established that take into consideration the unique characteristics of pervious concrete. Standardization or referencing to these techniques is crucial for comparison of most characteristics and for design criteria of pervious concrete systems. The most common quality control tests for conventional concrete are slump, unit weight, plastic air content, and compressive strength. Of those tests, only ASTM C1688/C1688M for density and void content of freshly mixed pervious concrete exists. There is a substantial need to develop modifications or surrogates to the other most common tests for conventional concrete.

Further research is needed to understand and improve the strength of pervious concrete. The ability of pervious concrete to withstand heavy vehicular loads (typical delivery truck or highway traffic) would enhance its use in a wide range of applications. There has been some research into the compressive and flexural strengths of some pervious concretes (Yang and Jiang 2003; Neithalath 2004; Marolf et al. 2004; Wimberly et al. 2001; Crouch et al. 2003; Zouaghi et al. 2000). Delatte et al. (2007) measured the porosity and strength of several cores removed from in-service pervious concrete pavements. There are many different variations and applications; however, for pervious concrete, the strength is dependent on porosity (Neithalath 2004; Marolf et al. 2004; Mulligan 2005; Montes and Haselbach 2006; Kevern et al. 2008a). ASTM C39/C39M has not proven to be an effective means of measuring compressive strength. Rodding to remove entrapped air is not appropriate for pervious concrete. Field placement techniques can also develop vertical porosity distributions in the pervious pavement, which may have impacts on the flexural strength and other characteristics (Haselbach and Freeman 2006). Additional research is needed to confirm that applicable 28-day strengths can be reliably achieved in production applications and into the various applications and strength characteristics of pervious concrete.

While pervious concrete is used more often for stormwater management in the United States, interest in pervious concrete in other parts of the world has focused on wearing course applications. Europe, Japan, and Australia have investigated pervious concrete for roadway use for noise reduction (Neithalath 2004) and improved skid resistance during rain events (Wang et al. 2008). Pervious concrete in these cases is placed using either the wet-on-wet method, where pervious concrete is placed overtop of fresh conventional concrete, or as a surface to precast concrete panels. The quietest pave-

ment in the world is a section of roadway in the Netherlands composed of precast concrete sections containing a pervious concrete wearing course. There is concern about using pervious concrete for road surfaces where traditional impervious designs avoid water seepage into the subbase, as this may undermine the subbase and, therefore, lose critical structural support under the impervious pavements. Much of this loss of material in the subbase, however, is due to hydrostatic forces in this area of water seepage that occur from point loads from vehicle wheels on the surface that push the soils away. Pervious concrete would of course allow for water seepage into the subbase, as water infiltration is its intention. This may not, however, have the same destructive hydrostatic forces on the subbase, as the water could also move vertically in the pervious column. Research into the water impacts on strength and the underlying soils for additional applications of pervious concrete as road surfaces is needed.

Field quality control and assurance tests need to be established. Methods for testing workability or consistency, such as the slump test for plain concrete, are necessary quality control tools for the concrete producer, as are tests for compressive strength and air entrainment. An owner's quality assurance tests for strength and durability are significant needs for pervious concrete pavements. Currently, ASTM C1688/C1688M exists to determine the fresh density, which can be related to the concrete production consistency. Although unit weight is often specified, no standard relationship exists between fresh density and hardened density. Additionally, the pervious concrete industry does not have a good understanding of the expected and allowable variability of the hardened in-place density. There are also testing methods that need to be developed for pervious concrete that are not similar to any methods traditionally used in the concrete industry. In addition, pollutant removal testing methods would be beneficial to design and specify pervious concrete for its potential water quality benefits.

11.4—Nondestructive determination of performance and properties

One of the significant impediments to the widespread use of pervious concrete is the absence of test methods to evaluate or predict the performance of the material as placed and in service. Due to its open pore structure, conventional methods of concrete performance estimation are not applicable to pervious concrete. Of late, some novel test methods have been attempted for nondestructive pervious concrete property estimation. Because it is easy to saturate a pervious concrete specimen with an electrolyte of known electrical conductivity, the emphasis has been on using electrical property-based methods for performance estimation. The use of a modified parameter that can be derived from electrical conductivity has been used to accurately predict the permeability of pervious concrete (Neithalath et al. 2006). Similar methods have also been extended to predict the acoustic absorption behavior of pervious concrete. Delatte et al. (2007) used ultrasonic pulse velocity (UPV) to investigate in-service pervious concrete pavements as well as extracted cores. Ultrasonic pulse velocity was found to correlate well with engineering properties such as strength and porosity.

11.5—Stormwater management

11.5.1 *Volume control*—There are two important aspects to stormwater management: runoff control and water quality control. There have been several initial studies into the infiltration rates, hydraulic conductivity, and rational runoff coefficient for pervious concrete (Wanielista et al. 2007; Montes and Haselbach 2006; Wimberly et al. 2001; Valavala et al. 2006). Additional study is needed for infiltration through sloped pervious concrete surfaces and the variation of infiltration rates with aging and other environmental impacts.

11.5.2 *Quality control*—Water-quality issues for watersheds are increasingly important. Much of the material washing into streams, rivers, and eventually into groundwater comes from surface runoff contaminated with materials applied to the ground surface. The contaminants can be excess fertilizers and nutrients, pesticides, road salts, or other materials intentionally applied; from spills or debris such as gasoline and petroleum products from oil drips; and tire abrasion or other residue such as litter, animal waste, and fine dust. Some materials are quickly picked up or dissolved and carried by runoff while others, including insoluble greases and low-volatile-content oils, may not.

Another source of runoff contaminant has been ineffective or unenforced control of runoff on bare earth, often from sites under development. Lack of effective erosion controls has resulted in significantly increased sediment loads in some areas. By controlling excess surface runoff using a properly designed pervious concrete pavement system, a reduction in peak stream velocity is possible. Erosion of streambeds is reduced, thereby reducing the sediment load carried by the stream. Washing large amounts of nutrients (compounds high in nitrogen and phosphorus) into the watershed has numerous consequences. Plant growth, particularly microbial biomass such as phytoplankton and algal blooms, is increased. Although plants produce oxygen while alive, when they die, they decay, using up available dissolved oxygen and increasing the biochemical oxygen demand (BOD). Creating or increasing BOD stress can, under the most extreme conditions, lead to events such as fish kills. Plant growth in pervious concrete systems should be minimal due to the lack of sunlight. In many cases, but not in all, the initial stormwater runoff will carry a higher concentration of contaminants than later runoff. The initial rain will wash off the surface somewhat. The part of the runoff with a higher contaminant concentration is termed the first flush and refers to the idea that approximately 90% of the pollutants are carried away in the first 1 in. (25 mm) of typical significant rain events (Leming et al. 2007). In arid areas with long periods between rain, a seasonal first flush may also occur. One of the common goals of runoff control is to capture the first flush. This is particularly true when dealing with small catchment (drainage) areas.

The first flush may not occur in some of the following cases:

(a) Large catchment areas rarely show a first flush, as a steady stream of the first flush of areas farther and farther away from the outlet arrive over time.
(b) There may not be a first flush if pollutants are not easily washed away or dissolved.
(c) Differences in pollutant load over time may be difficult to detect if the supply of pollutants is essentially continuous (for example, sediment from bare, easily eroded ground).

Relatively simple rules of thumb for selecting or approving designs and control features have often been used due to lack of sufficient local data combined with seasonal variations or effects and antecedent rainfall events. As a crude rule of thumb, the first flush occurs during the first 30 minutes to 1 hour for small sites, such as parking lots. When pervious concrete is used, the first hour of rain will generally be captured as a minimum. It is reasonable to assume that, at a minimum, the part of the runoff with the highest pollution load will also be captured. Pervious concrete pavements will carry the first flush into the pores of the concrete, and additional rain will carry the pollutants further into the system without returning them to the runoff stream. The natural cleaning effects of soil may then further clean the runoff. The adoption of specific types of mitigation devices and features depends on the site use, the types and quantities of pollutants anticipated, the estimated runoff, and site characteristics. While capturing the first flush of an area is often desirable, the disposal of the first flush can be technically challenging and expensive.

Research is needed to establish or confirm many of the observations and assumptions regarding pollution trapped by pervious concrete pavements (Rushton 2000). Several of the assumptions related to water quality that need to be confirmed are:

(a) Greases and low-volatile-content oils occurring routinely on parking areas, such as oil drips from vehicles, will probably be adsorbed onto the surface or into the pores of the pervious concrete, or will be degraded by the microbial community in the system (Pratt et al. 2002) and will not be transferred to groundwater or surface water in any significantly different quantities than with detention ponds. Recent studies have investigated the efficiency of pervious concretes in containing vehicular oil spills (Bhayani et al. 2007; Deo et al. 2008). Pervious concrete mixtures with porosities ranging from 13 to 25% were proportioned using two different-size aggregates. The oil retention and recovery were experimentally determined on 2 in. (50 mm) slices of pervious concrete specimens using a partition gravimetric method. An idealized pore-aperture model was used to develop a modeling framework for the oil retention in pervious concrete. The material parameters, as well as the input features that are most likely to influence the retention and recovery of oil, were identified. A genetic programming-based model was used to predict the oil retention in pervious concrete specimens. It was found that this modeling methodology provides good estimates of oil retention.
(b) Water carrying dissolved solids and nutrients into the soil from the pervious concrete will undergo natural filtering and purification such that the water reaching the groundwater table will be of roughly the same quality as runoff soaking in directly from the surface.
(c) The maximum draw-down time for a pervious concrete system should be 3 to 5 days, which is consistent with detention pond design, and may occur with pervious concrete pavements constructed on clayey soils. As light is not available past the surface, growth and subsequent decomposition of biomass due to high nutrient loads in the runoff will be minimal. As pervious concrete is not saturated for much of its service life, the pores are relatively small but not capillary in size, air is available to a large surface area compared with the volume, and there is little difference in the decomposition of biodegradable organic material compared with decomposition on the surface.

In addition to its potential for filtering or remediating stormwater-related pollutants (Tamai et al. 2004), there is interest in pervious concrete as a material for other environmental filtering or remediation purposes, especially in the agricultural and waste treatment industries. Pervious concrete has already been used for greenhouse floors. There is also interest in using pervious concrete as a paved surface for manure or sludge dewatering.

11.6—Urban heat island effect, carbonation, and other thermal properties

Conventional, dark pavement surfaces are large contributors to the urban heat island effect. There is a unique aspect of pervious concrete that may influence its impact on the urban heat island effect—its porous nature. Many porous media are insulators, and pervious concrete may have some of these characteristics. Pervious concrete, however, also consists of interconnected voids that may influence convection of heat into or out of the earth's surface. It is unknown which heat transfer processes dominate, and under what conditions. There is little or no research into the urban heat island impacts of using pervious concrete over other impervious pavement surfaces; therefore, additional information is greatly needed (Ferguson 2005). Similarly, the thermal aspects of pervious concrete may be important for determining remediation rates and other environmental process rates.

The use of pervious concrete may also have an impact on another aspect related to the global climate. There has been much research and concern about the levels of carbon dioxide in the atmosphere. Many researchers have performed life-cycle analyses of the contribution to the carbon dioxide in the atmosphere from many construction materials. Concrete has been shown to be a contributor in two ways: the first is in the energy use for making cement, if the energy source is a nonrenewable source; and the second is in the chemical process that forms cement from its source materials, which releases carbon dioxide as a by-product. Therefore, even if the carbon dioxide component from the energy use was eliminated, the manufacture of pervious concrete would still

result in a net production of carbon dioxide. Carbon dioxide can be absorbed back into concrete structures over time. This process, referred to as carbonation, involves a chemical change and can balance some of the carbon dioxide gain from the cement manufacturing process. Carbonation is usually slow under ambient conditions, but faster when traditional concrete has large surfaces exposed to the air. An example is when concrete is broken up and recycled for fill. Pervious concrete has a much larger surface area exposed than other concrete applications to the air and may have a faster rate of carbonation. Research into this rate is needed so that the overall impact of using pervious concrete on the amounts of carbon dioxide in the atmosphere can be better understood.

11.7—Construction, operation, and maintenance needs

11.7.1 *On-site handling and adjustments*—Conventional wisdom and best practice for traditional concrete is to not add water on site. In pervious concrete, it is preferable and beneficial to have sufficient workability to achieve the designed void content rather than merely maintaining a specified *w/cm*. There is a need to systematically evaluate when and how much water can be added on site and identify when the additions begin to negatively influence the final product.

11.7.2 *Finishing operations and curing*—Traditionally, pervious concrete was placed higher than finish elevation using a spacer strip, which was removed prior to compacting with a weighted roller. It was observed that the extra step allowed time for the surface to dry and resulted in many placements with less-than-desirable surface durability. The most common method of compaction and finishing is multiple passes with a roller screed. However, new finishing techniques, including laser screeds and rotating float pans, are being used. Research is needed to evaluate these new techniques and compare with the status quo. Many older pervious concrete sections were installed in multiple lifts. The industry gravitated toward single-lift installations due to expediency and concerns over clogging between the lift interface. However, it is well-understood that compaction varies with depth during installation, with some pavements having very low density at the bottom (Haselbach and Freeman 2006). Research is needed to revisit appropriate lift thicknesses for various compaction techniques and the potential need for multiple lift installations in certain instances.

One change to pervious concrete mixtures and construction techniques is the inclusion of internal curing techniques to reduce curing requirements. When super-absorbent polymers (SAPs) or prewetted lightweight aggregates are used in pervious concrete mixtures, curing under plastic sheeting may be reduced (Kevern and Farney 2012). Additional techniques such as applying surface densifiers to fresh and hardened pervious concrete have also shown to be viable techniques for eliminating curing under plastic without sacrificing surface durability (Kevern and Sparks 2013). When curing techniques other than plastic sheeting are first used in a local area, test placements are highly recommended to ensure proper curing of the pervious concrete.

11.7.3 *Surface deterioration and repair*—Typical concrete surface treatments may not be applicable to pervious concrete, as many are surface sealants and may effectively impact the infiltration capability of the pervious pavement. Concrete pavers over pervious concrete may be used for increased winter durability. Research is not only needed for surface treatments that can extend the life of a pervious concrete pavement and add to its sustainability and aesthetics, but for materials and methods for pavement repair as well. Joints, either installed using a pizza cutter or sawn, are a perennial point of weakness and deterioration in pervious concrete. The industry has long suggested not sealing joints; however, anecdotal evidence suggests that sealing joints prevents deterioration from incompressibles. Research is needed to determine the potential impacts for various joint installation methods and treatments.

11.8—Other novel applications and uses

There are many other novel applications for pervious concrete other than as pavement surfaces for stormwater control or as an environmental filter for dewatering processes. Its lower density may benefit its use in building construction to reduce structural needs. One major consideration for structural use is the need for and performance of reinforcing steel. Although two structural-steel-reinforced pervious concrete walls in Chicago have shown excellent performance after 100 years (Seegebrecht 2015), research is needed to verify steel design criteria and bonding behavior in addition to durability.

Pervious concrete is sometimes referred to as enhanced-porosity concrete and has been shown to have some benefits in sound absorption. Some applications are as road surfaces and sound barriers (Neithalath et al. 2005a; Tamai et al. 2004; Neithalath 2004; Schaefer et al. 2010).

11.8.1 *Porous grout*—The technology of grout injection to provide structural support beneath foundations has been practiced in construction since 1802 (Houlsby 1990). The materials have traditionally been a mixture of portland cement; water; and often a filler, such as sand. This is mixed into slurry and pumped into the desired area, usually the interface between existing foundations and the in-place soil or rock, forming a structural bond that is rigid and not normally pervious. There are cases, however, in which hydraulic conductivity is desired so that the natural hydrostatic forces can be relieved without causing deterioration due to saturation, erosion, and piping. This has led to the widespread use of French drains (gravel), drainage blankets, and fabrics for drainage and prevention of erosion (geotextiles), where foundations are accessible during construction. This type of pumped-in-place pervious grout would fill a basic need in the construction industry, particularly in projects involving site remediation and retrofit. Example applications of this pumped, porous material include remediation of dams (Weaver 1991), tunnels, highways, canals, railroads, and environmental treatment. Porous grout materials that could be pumped were studied (Yen et al. 2002). The studies encompassed a wide range of pumped materials that had drainage properties.

CHAPTER 12—THE ENVIRONMENT AND PERVIOUS CONCRETE

Pervious concrete systems are recognized as best management practices (BMPs) for stormwater management by the U.S. EPA and permit-granting agencies. Pervious concrete systems also support other sustainable development initiatives such as the EPA Heat Island Reduction Initiative (U.S. EPA 2022a) and Low Impact Development (U.S. EPA 2022b). Pervious concrete provides several environmental qualities sought by sustainable assessment organizations such as USGBC's LEED rating system for sustainable building construction (U.S. Green Building Council 2013) and the Institute for Sustainable Infrastructure's Envision program (ISI 2022). Stormwater management is especially important in urban civil infrastructure projects, and pervious concrete is potentially a key component (Fig. 12).

The stormwater storage capacity within and below pervious concrete pavement systems can be used to slow the stormwater peak flow. The volume of stormwater runoff can be reduced through infiltration into the underlying soil below the pervious concrete pavement, detention and evaporation, or both. Reduction in total runoff volume provides a reduction in associated pollutants from the system into streams, rivers, lakes, and oceans. By infiltrating the stormwater, not only is the volume of stormwater greatly reduced, but pervious concrete effectively provides water quality treatment for the first flush. Even when used as a stormwater detention system, pervious concrete provides not only the peak flow mitigation benefits, but also provides stormwater quality concrete.

The filtration provided by the voided matrix or the underground aggregate storage bed within pervious concrete systems can retain organic pollutants and naturally occurring microbial growth may provide treatment before the pollutants that remain are eventually converted by native soils if infiltrated or conveyed through underdrains. Pervious concrete also collects total suspended solids (TSS), which are considered one of the main pollutants in stormwater runoff (U.S. EPA 1999; Mata and Leming 2012). In addition, the pervious concrete layer may effectively reduce the concentration of many metals found in stormwater runoff. This is through the retention of metals bound to particulates and through chemical removal of metals in the dissolved phase. This process is by an adsorption or ion exchange process within the pervious concrete matrix. Some of the dissolved metals that are treated include zinc, copper, lead, and cadmium. These metals are common in highway runoff and are important to be controlled when stormwaters are discharged to sensitive waters such as those supporting salmonid species (Haselbach et al. 2014a,b; Holmes et al. 2017).

Fig. 12—Pervious concrete stormwater management system.

The infiltration provided by pervious concrete potentially recharges groundwater, provides irrigation to nearby surface vegetation and tree root systems, and mitigates thermal pollution in a receiving body of water. Thermal pollution occurs when rain lands on hot pavement and the associated runoff may significantly contribute to the increase in water temperatures negatively affecting the habitat of fish, aquatics, and vegetation within various bodies of water. The potential to harvest water for a variety of purposes is also enhanced, when permitted by local regulation.

Pervious concrete absorbs and retains less heat than most conventional pavement, giving it the potential to positively impact the urban heat island. The reason for this is that the relatively open pore structure of pervious concrete may store and transmit less heat, therefore helping to lower heat island effects in urban areas (Kevern et al. 2009a; Haselbach et al. 2011). In addition, the water stored in the pervious concrete layer after a precipitation event may aid in heat island reduction through evaporative cooling (Lorenzi et al. 2015).

CHAPTER 13—REFERENCES

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The American Concrete Institute (ACI) is a leading authority and resource worldwide for the development and distribution of consensus-based standards and technical resources, educational programs, and certifications for individuals and organizations involved in concrete design, construction, and materials, who share a commitment to pursuing the best use of concrete.

Individuals interested in the activities of ACI are encouraged to explore the ACI website for membership opportunities, committee activities, and a wide variety of concrete resources. As a volunteer member-driven organization, ACI invites partnerships and welcomes all concrete professionals who wish to be part of a respected, connected, social group that provides an opportunity for professional growth, networking and enjoyment.

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