ACI 522R-10

Report on Pervious Concrete

Reported by ACI Committee 522

American Concrete Institute®

First Printing
March 2010

American Concrete Institute®
Advancing concrete knowledge

Report on Pervious Concrete

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised *ACI Manual of Concrete Practice* (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

ISBN 978-0-87031-364-6

Report on Pervious Concrete

Reported by ACI Committee 522

Matthew A. Offenberg
Chair

Don J. Wade
Vice Chair

Charles A. Weiss Jr.
Secretary

William L. Arent, Bob J. Banka, William D. Brant, Heather J. Brown, Manoj Chopra, Michael S. Davy, Norbert J. Delatte, Aly Ibrahim Eldarwish, Bruce K. Ferguson, Dale Fisher, Bruce A. Glaspey, Liv Haselbach, Omer Heracklis, Daniel J. Huffman, Frank Lennox, John R. Love III, Kamyar C. Mahboub, Narayanan Neithalath*, Scott M. Palotta, Joseph A. Rottman, George W. Seegebrecht, David M. Suchorski, Diep T. Tu, Robert Louis Varner, Marty Wanielista, W. Jason Weiss, Peter T. Yen

*Chair of editorial subcommittee.

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/ft^2 (81 to 730 L/min/m^2). 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

ACI 522R-10 supersedes ACI 522R-06 and was adopted and published March 2010.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

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 (Fig. 1.1), 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/ft^2 (81 to 730 L/min/m^2) or 192 to 1724 in./h (0.14 to 1.22 cm/s).

1.2—Scope

Concern has been growing in recent years toward reducing the pollutants in water supplies and the environment. In the

Fig. 1.1—Pervious concrete pavement texture on parking lot.

1960s, engineers realized that runoff from developed real estate had the potential to pollute surface and groundwater supplies. Further, as land is developed, runoff leaves the site in higher rates and volumes, leading to downstream flooding and bank erosion. Pervious concrete pavement reduces the impact of development by reducing or eliminating storm-water runoff rates and protecting water supplies.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = area of the pavement, acre (m^2)
b = solid volume of coarse aggregate in a unit volume of concrete, ft^3 (m^3)
b_o = solid volume of coarse aggregate in a unit volume of coarse aggregate, ft^3 (m^3)
b/b_o = dry-rodded volume of coarse aggregate in a unit volume of concrete
C = runoff coefficient
c = cement content, lb (kg)
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, seconds
h_1 = initial head, in. (mm)
h_2 = final head, in. (mm)
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
V_a = aggregate volume, ft^3 (m^3)
V_c = cement volume, ft^3 (m^3)
V_P = paste volume; total of cement and water volume, 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)
V_s = total solid volume of aggregate, cement, and water, ft^3 (m^3)
V_{tot} = total volume, ft^3 (m^3)
V_w = water volume, ft^3 (m^3)
W_a = dry aggregate weight, lb (kg)
W_{ssd} = saturated surface-dry weight, lb (kg)
w = water content, lb (kg)
α = absorption coefficient

2.2—Definitions

ACI provides a comprehensive list of acceptable definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided here complement that resource.

concrete, pervious—hydraulic cement concrete proportioned with sufficient interconnected voids that result in a highly permeable material, allowing water to readily pass.

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

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

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

porosity—the volume of open and connected interstitial void space in pervious concrete.

raveling—the wearing away of the concrete surface caused by the dislodging of 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 has been used in a wide range of applications, including:

- Pervious pavement for parking lots (Fig. 3.1);
- Rigid drainage layers under exterior mall areas;
- Greenhouse floors to keep the floor free of standing water;
- Structural wall applications where lightweight or better thermal insulation characteristics, or both, are required;
- Pavements, walls, and floors where better acoustic absorption characteristics are desired;
- Base course for streets, roads, driveways, and airports;
- Surface course for parks and tennis courts;
- Floors for zoo areas and animal barns and stalls;
- Bridge embankments;
- Swimming pool decks;

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

- Beach structures and seawalls;
- Sewage treatment plant sludge beds;
- Solar energy storage systems;
- Wall linings for drilled water wells; and
- Artificial reefs where the open structure of pervious concrete mimics the reef structure.

Typically, unreinforced pervious concrete is used in all these applications because of the high risk of reinforcing steel corrosion due to the open pore structure of the material.

3.2—Building applications: history

Pervious concrete has been used in building construction since at least the middle of the nineteenth century (Francis 1965). 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 multistory 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 (UK). 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. By 1942, pervious concrete had been used to build over 900 houses.

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). Pervious concrete used less cement per unit volume of concrete as compared with conventional concrete, and the material was advantageous where manpower was scarce or expensive. Over the years, the pervious concrete system contributed substantially to the production of new houses in the UK, Germany, Holland, France, Belgium, Scotland, Spain, Hungary, Venezuela, West Africa, the Middle East, Australia, and Russia. 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. 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. 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.

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—Pervious concrete pavement used within the drip line of tree.

Pervious concrete was extensively used for industrial, public, and domestic buildings in areas north of the Arctic Circle because traditional building materials proved impracticable. Examples of these impracticalities include the high transportation costs of brick, fire hazards of timber, and poor thermal insulation properties of plain concrete (Malhotra 1976).

Although pervious concrete has been used in Europe and Australia for the past 60 years, its 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.

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

Pervious concrete pavements' advantages over conventional concrete pavements include:

- Controlling stormwater pollution at the source;
- Increasing facilities for parking by eliminating the need for water-retention areas;
- Controlling stormwater runoff;
- Reducing hydroplaning on road and highway surfaces;
- Creating additional lift to aircraft during takeoff due to the cooling effect;
- Reducing glare on road surfaces to a great extent, particularly when wet at night;
- Reducing the interaction noise between tire and pavement;
- Eliminating or reducing the size of storm sewers; and
- Allowing air and water to reach tree roots, even with pavement within the tree drip line (Fig. 3.2).

Pervious concrete pavements' potential disadvantages and challenges include:

- Limited use in heavy vehicle traffic areas;
- Specialized construction practices;
- Extended curing time;
- Sensitivity to water content and control in fresh concrete;
- Special attention and care in design of some soil types such as expansive soils and frost susceptible ones;

- Lack of standardized test methods; and
- Special attention possibly required with high groundwater.

Engineers have specified pervious concrete in pavements as:

- Surface course;
- Permeable base and edge drains; and
- Shoulders.

The success of pervious pavement systems has been mixed. In some areas, pervious concrete pavement systems have been applied successfully, whereas in others they have clogged in a short time. Many failures can be attributed to contractor inexperience, higher compaction of soil than specified, and improper site design. For a pervious concrete pavement to work successfully:

- Permeability of soils should be verified. A percolation rate of 0.5 in./h (13 mm/h) and a soil layer of 4 ft (1.2 m) or more are generally recommended. There are installations of pervious concrete and other porous paving materials. In the red-clay Piedmont regions of the Carolinas and Georgia, however, where the subgrade infiltration rate is much less than 0.5 in./h (13 mm/h), these pavements facilitate infiltration and filtering of runoff and recharging of groundwater (although they do not infiltrate all of the rain water in large storms);
- Construction site runoff and heavy equipment should be kept 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; and
- 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.

3.3.1 *Surface course*—Pervious concrete may be used as a surface course for parking lots and minor road strips (Fig. 3.1). Use in the U.S., to a large extent, has been in surface courses. Many parking lots in Florida consist of a pervious concrete surface course. Its use in Florida is due to three factors:

1. Florida frequently encounters heavy storms that cause a quick accumulation of large amounts of stormwater; the use of pervious concrete reduces the runoff volume;
2. Designers prefer the stormwater be retained on-site to recharge the groundwater system; and
3. The cost effectiveness of using pervious concrete over conventional pavements is greatly enhanced with the elimination of storm sewers.

3.3.1.1 *Parking lots*—Pervious concrete was referred to as a parking lot paving material in the central Florida area 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) has 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. Pervious concrete parking lots have also been selected as an integral solution to the problem of hot pavements in the Cool Communities program. The air temperature over pervious concrete parking lots is generally cooler than asphalt. Pervious concrete parking lots also reduce snow and ice buildup and are considered a nonpollutant to the environment. The practical range of design thicknesses for pervious concrete pavements is from 5 to 12 in. (125 to 300 mm) for plain parking lots.

3.3.1.2 *Roadways*—Pervious concrete for roadways is usually considered for two applications as a:

1. Drainable base, or subbase material; and
2. Roadway surface or friction course.

In both categories, although the drainage characteristics are required properties, strength requirements may vary depending on the location of the material in the pavement section. The practical range of design thicknesses for pervious concrete is from 6 to 12 in. (150 to 300 mm) for plain roadway pavements. Bonded overlays (Maynard 1970), however, have been as thin as 2 in. (50 mm). Many highways in Europe are being constructed using an overlay of latex-modified pervious concrete that allows for pavement drainage and tire-noise reduction. The latex modification results in better mechanical properties (Pindado et al. 1999).

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. 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 used in conjunction with a nonwoven geotextile fabric. A similar system can be used in slope stabilization.

3.3.3 *Shoulders*—Pervious concrete shoulders have been used in France in an effort to reduce pumping beneath concrete pavements. Air-entraining admixtures are used to increase resistance to freezing and thawing. Porosities on the order of 15 to 25% have been found to nearly eliminate the risk due to freezing, unless the concrete is allowed to become saturated. Compressive strengths are often less than 2000 psi (14 MPa) at 28 days.

3.4—Other applications

3.4.1 *Drains*—Water and power resources 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 served 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 a gravel base to the edges of the slab. Fly ash is included in some of the mixtures to increase the workability.

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. This open-graded structure tends to absorb and dissipate the sound in the material rather than reflecting it to another location.

CHAPTER 4—MATERIALS

4.1—General

Pervious concrete, also known as no-fines, permeable, or enhanced porosity concrete (EPC), usually consists of normal portland cement, uniform-sized coarse aggregate, and water. This combination forms an agglomeration of coarse aggregates surrounded by a thin layer of hardened cement paste at their points of contact. 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. Such porous concrete can be classified into two types: one where the porosity is present in the aggregate component of the mixture (lightweight aggregate concretes), and one where porosity is introduced in the nonaggregate component of the mixture (pervious concrete) (Neithalath 2004). Lightweight aggregate concrete can be constructed by using extremely porous natural or synthetic aggregates. Pervious concrete has little or no fine aggregate in the mixture. Another distinction between these two types of porous concrete is based mainly on the void structure. Lightweight aggregate concretes contain large percentages of relatively nonconnected 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

Aggregate gradings used in pervious concrete are typically either single-sized coarse aggregate or grading between 3/4 and 3/8 in. (19 and 9.5 mm). Rounded and crushed aggregates, both normal and lightweight, have been used to make pervious concrete. The aggregate used should meet requirements of ASTM D448 and C33/C33M. Fine aggregate content is limited in pervious concrete mixtures because it tends to compromise the connectedness of the pore system. The addition of fine aggregate may increase compressive strengths and density but correspondingly reduce the flow rate of water through the pervious concrete mass.

Aggregate quality in pervious concrete is equally important as in conventional concrete. Flaky or elongated particles should be avoided. The narrow-graded coarse aggregate should be hard and clean, and free of coatings, such as dust or 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. Unit weights of aggregates should be determined in accordance with ASTM C29/C29M.

For new, unknown aggregate sources, results of tests conducted as per ASTM C33/C33M and D448 should be reviewed with the input of an experienced materials engineer. Examining untested samples by an experienced petrographer can prove to be invaluable in identifying characteristics such as quality, hardness, 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. Otherwise, a 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, C595/C595M, or C1157/C1157M is used as the main binder. Supplementary cementitious materials such as fly ash, ground-granulated blast-furnace slag, and silica fume can also be used in addition to portland cement and should meet the requirements of ASTM C618, C989, and C1240, respectively. Testing materials in trial batching is strongly recommended to verify that cement-admixture compatibility is not a problem 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 material ratio (*w/cm*) (typically 0.26 to 0.40) because an excess amount of water will lead to drainage of the paste and subsequent clogging of the pore system. The addition of water, therefore, has to 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.

4.5—Admixtures

Water-reducing admixtures should meet the requirements of ASTM C494/C494M. Water-reducing admixtures (high-range or medium-range) are used depending on the *w/cm*. Retarding admixtures are used to stabilize and control cement hydration. Retarding admixtures are frequently preferred

when dealing with stiff mixtures, such as pervious concrete. They are especially useful in hot weather applications. Retarding admixtures can act as lubricants to help discharge concrete from a mixer and can improve handling and in-place performance characteristics. Accelerators can be used when pervious concretes are placed in cold weather. Studies report the use of cement hydration stabilizers as an aid in extending the working time of the mixture and viscosity-modifying admixtures (VMAs) to enhance workability; these advantages have also been witnessed during actual production and placements for projects. With the use of multiple admixtures in any concrete mixture, it is recommended that a trial mixture placement is conducted to identify any admixture incompatibility problems and verify desired fresh and hardened properties are consistently achievable.

Air-entraining admixtures should meet the requirements of ASTM C260. Air-entraining admixtures are not commonly used in pervious concretes, but can be used in environments susceptible to freezing and thawing. No reliable method exists, however, to quantify the entrained air volume in these materials. Research is currently underway on the resistance to freezing and thawing of pervious concrete mixtures, and most studies involve the use of an air-entraining agent (Neithalath et al. 2005a; Schaefer et al. 2006; Baas 2006). Until a greater body of research is available, it may be prudent to include an air-entraining admixture where placement occurs in colder climates. This is reportedly true in relatively higher cement content mixtures where the paste thickness coating aggregate particles exceeds 0.008 in. (200 μm). Incorporation of fibers for mixtures to be exposed to freezing and thawing has shown success in some studies to improve durability in cold climates.

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 be helpful in this regard.

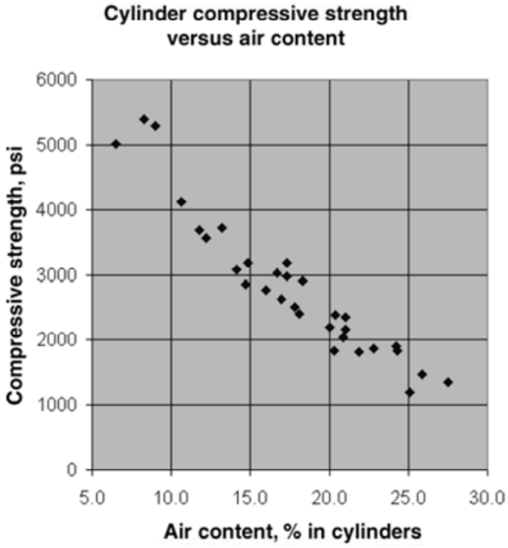

Fig. 5.1—Relationship between air content and compressive strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

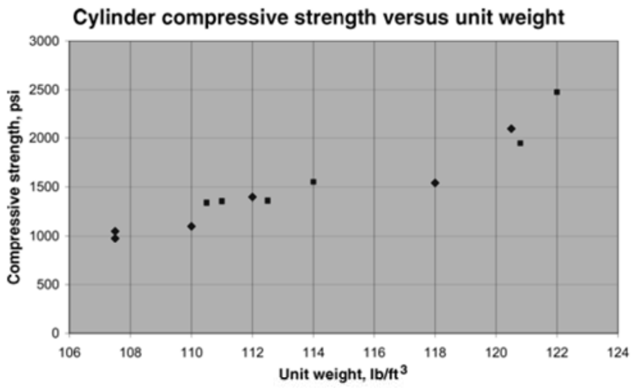

Fig. 5.2—Relationship between unit weight and compressive strength for pervious concrete (Mulligan 2005) (1 psi = 0.006895 MPa; 1 lb/ft^3 = 16.02 kg/m^3).

CHAPTER 5—PROPERTIES

5.1—General

The various properties of pervious concrete are primarily dependent on its porosity (air void content), which in turn depends on cementitious content, *w/cm*, compaction level, and aggregate gradation and quality. The pore sizes in the material also impact strength properties. Although pervious concrete has been used for paving for more than 20 years in the U.S., only a few investigations have been done to determine performance (Ghafoori 1995; Wanielista et al. 2007). Investigations have been based primarily on laboratory tests, with some data from actual field installations obtained. Only one ASTM method exists that is specifically intended for use on pervious concrete. ASTM Subcommittee C09.49 is developing test methods for compressive strength, flexural strength, in-place density/porosity, and in-place permeability. The specifier should use caution when referencing test methods for pervious concrete that are intended for plain concrete.

5.2—Compressive strength

The compressive strength of pervious concrete is strongly affected by the mixture proportion and compaction effort during placement. Figure 5.1 shows the relationship between pervious concrete compressive strength and air void content (Meininger 1988). Figure 5.1 is based on a series of laboratory tests where two sizes of coarse aggregate were used and compaction effort and aggregate gradation were varied. Figure 5.2 (Mulligan 2005) shows a relationship between pervious concrete compressive strength and unit weight. The figure is based on another series of laboratory tests where one size of coarse aggregate was used and compaction effort and the aggregate-cement ratio was varied. Figure 5.1 shows that relatively high compressive strengths of pervious concrete mixtures are possible, but the high strength is achieved only with the reduction of air void content. This results in a loss in percolating efficiency of pervious concrete. It has been reported that an 11% decrease in compressive strength was observed when the vibration

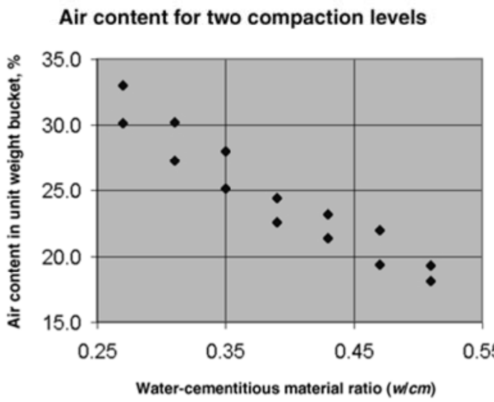

Fig. 5.3—Relationship between air content and compaction energy for pervious concrete (Meininger 1988).

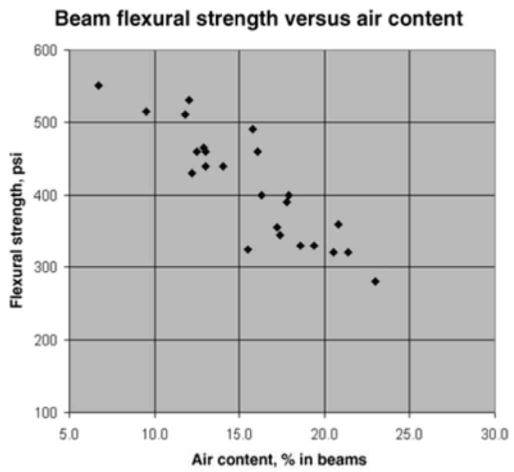

Fig. 5.4—Relationship between air content and flexural strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

amplitude of the compactor is reduced to 0.0034 in. (0.086 mm) from 0.005 in. (0.127 mm) (Suleiman et al. 2006). An increase in aggregate size has been reported to result in reduced compressive strength, while polymer additives and mineral admixtures have been found to increase the compressive strength for the same aggregate gradation (Jing and Guoliang 2003). Crouch et al. (2006) reports 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 properties. 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 and placement problems. Figure 5.3 (Meininger 1988) shows the relationship between the *w/cm* and air void content of a pervious concrete mixture

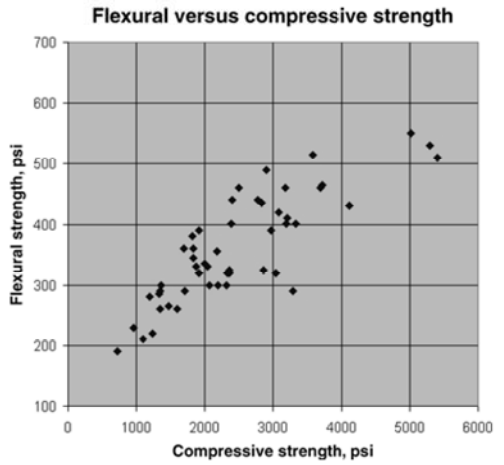

Fig. 5.5—Relationship between flexural strength and compressive strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

(with cement and aggregate content held constant) at two different compaction levels. Experience has shown that a *w/cm* of 0.26 to 0.45 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 of a pervious concrete mixture is 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 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 size chosen, binder drainage tests are recommended to be carried out to ascertain the optimum cementitious content (Nelson and Phillips 1994).

Another factor that can have a significant impact on the strength of pervious concretes is the thickness of the paste layer surrounding the aggregate. This is related to the aggregate size, cementitious material content, and the *w/cm*.

5.3—Flexural strength

Figure 5.4 (Meininger 1988) shows the relationship between pervious concrete flexural strength and air void content based on beam specimens tested in the same series of laboratory tests described for Fig. 5.1. Although these results are based on a limited number of specimens, comparing the data in Fig. 5.1 and 5.4 indicates that a relationship between the compressive and flexural strengths of pervious concrete exists. This relationship, like compressive strength, depends on several variables. Figure 5.5 (Meininger 1988) shows the relationship between compressive and flexural strengths of pervious concrete for one laboratory test series. Another series of test data relating the flexural strength and porosity is shown in Fig 5.6 (Neithalath 2004).

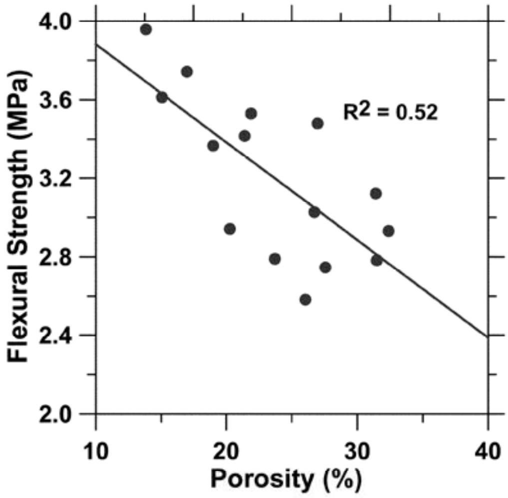

Fig. 5.6—Relationship between flexural strength and porosity for pervious concrete (1 psi = 0.006895 MPa).

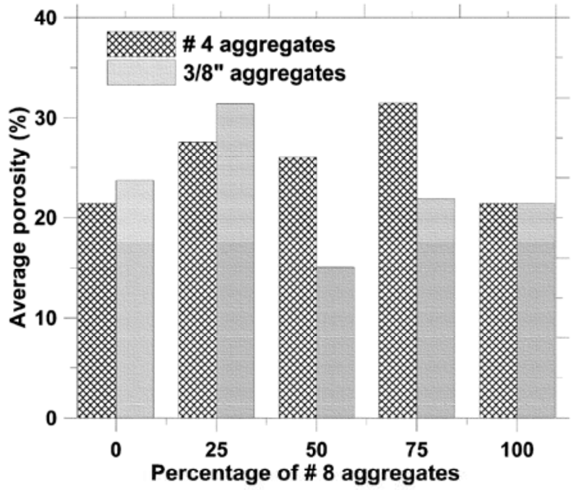

Fig. 5.7—Influence of aggregate size and gradation on the porosity of pervious concretes.

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 tensile strength of about 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).

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 Ahmad and Shah (1985) for precast concrete.

$$f_r = 2.3 {f_c'}^{2/3} \quad \text{(in.-lb units)} \tag{5-1}$$

$$f_r = 0.083 {f_c'}^{2/3} \quad \text{(SI units)}$$

5.4—Void content/density

The density of fresh pervious concrete can be determined by ASTM C1688/C1688M, and is directly related to the void content of a given mixture. Two additional methods that determine porosity of hardened pervious concrete have been reported (Neithalath 2004). The first method involves a volumetric procedure where the mass of water filling a sealed pervious concrete sample is converted into an equivalent volume of pores. In the second method, an image analysis procedure is employed on pervious concrete specimens that have been impregnated with a low-viscosity epoxy (Marolf et al. 2004). The accessible porosity in a pervious concrete mixture is a function of the aggregate sizes and relative quantities of different sizes in the mixture (Brite/Euram Report 1994). The image analysis procedure is advantageous in ascertaining the variation in porosity with depth of a pervious concrete specimen or layer.

Void content is highly dependent on several factors: aggregate gradation, cementitious material content, *w/cm*, and compactive effort.

The influence of aggregate gradation on porosity for laboratory prepared pervious concrete specimens is shown in Fig. 5.7. A range of porosities can be obtained by blending aggregates of two different sizes (Neithalath 2004). Care should be taken to ensure that the aggregate size ratio (ratio of the diameter of the larger aggregate to that of the smaller one) is not very large when using aggregate blends. If the ratio is very high (typically 2.5 or more), the smaller aggregate will fill the voids left by the larger one, reducing the porosity and, consequently, the permeability. Though the mechanical properties are enhanced using blends with large size ratios, it is generally not recommended because pervious concretes are primarily designed for water permeation.

Compactive effort has an influence on the void content, porosity, and density of a given pervious concrete mixture. In a laboratory test series (Meininger 1988), a single pervious concrete mixture compacted with eight different levels of effort, produced unit weight values that varied from 105 to 120 lb/ft^3 (1680 to 1920 kg/m^3). Figure 5.2 shows that this variation of unit weights and related air void content can have a measurable effect on the compressive strength of pervious concrete. For constant paste content, the void content is reported to be a function of compactive effort, aggregate particle shape and texture, and aggregate uniformity coefficient (Crouch et al. 2006).

5.5—Pore sizes

The sizes or size range of pores in pervious concrete is also a major factor influencing its properties. The influence of pore sizes on water permeability and acoustic absorption has been documented (Neithalath 2004; Neithalath et al. 2006). To generate larger-sized pores in the material, larger aggregate sizes are recommended. Larger-sized pores are recommended because they may reduce the chances of pore-clogging (Nelson and Phillips 1994). Figures 5.8 and 5.9 depict the influence of single-sized aggregates as well as blending two different aggregate sizes in varying proportions on the pore sizes of pervious concrete. Replacing smaller-sized aggregates with an increasing percentage of larger-sized ones increases

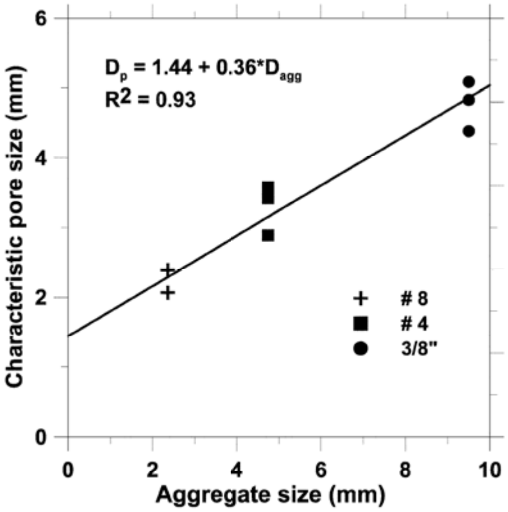

Fig. 5.8—Influence of aggregate size on the pore size of single-sized aggregate pervious concrete mixtures.

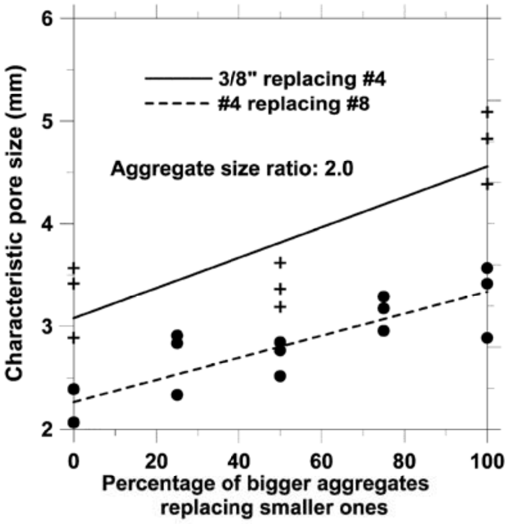

Fig. 5.9—Influence of aggregate blending on the pore size of pervious concrete.

the pore size. This is because the introduced coarser particle may not be able to fit in the void left by the removed finer particle (Neithalath 2004; Neithalath et al. 2003).

Pore structure of pervious concrete is instrumental in all the properties and performance characteristics of this material. Low et al. (2008) outlined a statistical approach to the determination of factors influencing pore structure features such as porosity and pore connectivity factor, and performance characteristic (permeability) of pervious concrete. Using a factorial design experiment with four factors (aggregate size, aggregate-cement ratio, *w/cm*, and sand-coarse aggregate ratio), 16 pervious concrete mixtures were proportioned. From a range analysis on the responses, only the first three of four factors mentioned dominate the measured responses. An image analysis method on two-dimensional sections of pervious concrete was used to characterize the pore structure. A two-parameter Weibull distribution was used to model the pore area and pore size distributions of pervious concrete.

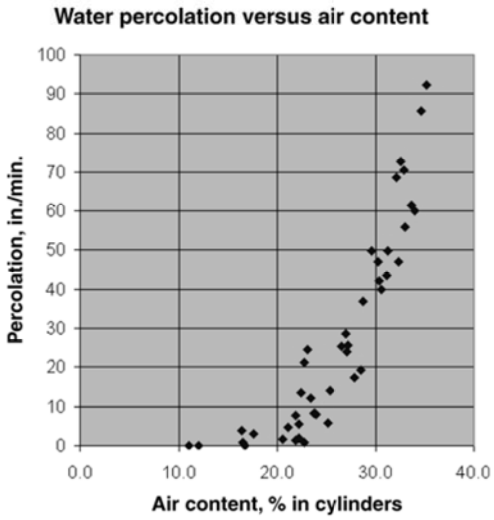

Fig. 5.10—Relationship between air content and percolation rate for pervious concrete (Meininger 1988) (1 psi = 0.06895 MPa).

The scale parameter of the Weibull distribution was used to describe the "characteristic pore area" or "characteristic pore size" of pervious concrete.

5.6—Percolation rate

One of the most important features of pervious concrete is its ability to percolate water through the matrix. The percolation 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 0.01 m/s (Brite/Euram Report 1994). Another study (Nissoux et al. 1993) reports a permeability of 0.88 gal./ft^2/s (36 L/m^2/s). Figure 5.10 (Meininger 1988) shows the relationship between the air void content and percolation rate of a pervious concrete mixture. Because the percolation rate 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 percolation rate and an acceptable compressive strength.

The permeability of pervious concrete can be measured by a simple falling-head permeameter as shown in Fig. 5.11 (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 drain pipe. 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. The equipment is calibrated for an initial head

of 11.6 in. (290 mm) and a final head of 2.8 in. (70 mm). 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 was also constructed for determining the permeability of pervious 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. A recent study (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. It is anticipated that the widespread use of techniques like X-ray-computed tomography will lead to accurate determination of pore connectivity in pervious concretes.

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 was 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.

5.7—Durability

Durability of pervious concrete refers to the service life under given environmental conditions. Physical effects that adversely influence the durability of concrete include exposure to temperature extremes and chemicals such as sulfates and acids. No research has been conducted on the resistance of pervious concrete to aggressive attack by sulfate-bearing or acidic water. The durability of pervious concrete under freezing-and-thawing conditions is becoming well documented; no documented deterioration due to freezing-and-thawing cycling in the field is known to exist.

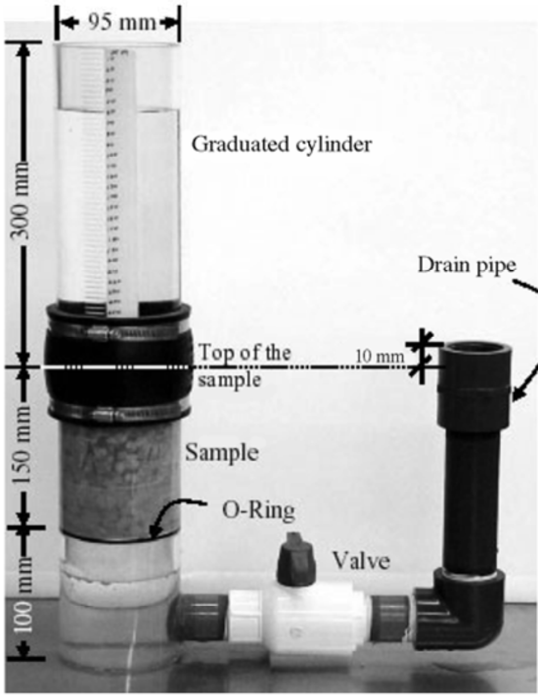

Fig. 5.11—Apparatus for measuring permeability of pervious concrete by a simple falling-head permeameter (Neithalath et al. 2003) (1 in. = 25.4 mm).

Limited testing in freezing-and-thawing conditions indicates poor durability if the entire void structure is filled with water (U.S. Bureau of Reclamation 1947). Other tests, however, have shown the pore structure being filled with water has some, but not complete, correlation with the overall results. A slower freezing condition—one cycle per day as compared with five or six as per ASTM C 666, Procedure A—may allow the water to drain from the pervious concrete, improving durability (Neithalath et al. 2005a). Limited field data exist on the long-term durability of pervious concrete in northern climates (Delatte et al. 2007); however, substantial empirical data support its use from a freezing-and-thawing resistance perspective in the Rocky Mountain and Sierra Nevada regions of the western U.S. along with other regions of the country where the standard practice is to treat conventional concrete pavements with air-entraining admixtures for the purposes of resistance to freezing and thawing. Caution should always be exercised when using pervious concrete in a situation where complete saturation before a hard freeze may occur.

Tests indicate that entraining air in the cement paste may improve resistance to freezing and thawing. In the laboratory under ASTM C666/C666M test conditions, non-air-entrained pervious concrete fails (relative dynamic modulus drops to less than 60%) in approximately 100 cycles of freezing and thawing in the chamber (ASTM C666/C666M requires a standard 300 cycles for the test). The relative

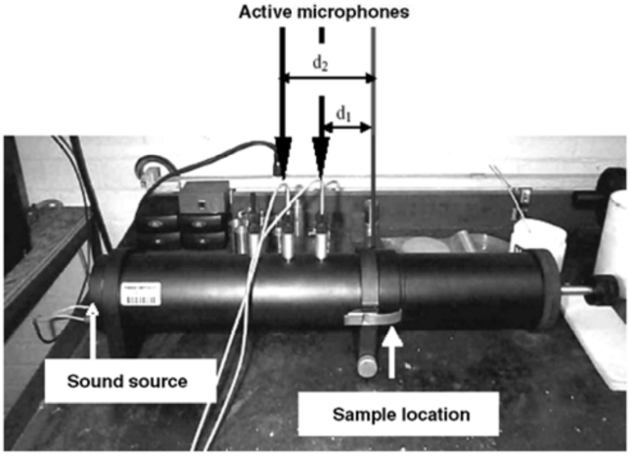

Fig. 5.12—Impedance tube for measuring the sound absorption characteristics of pervious concrete (Neithalath 2004; Marolf et al. 2004).

modulus stays well over 60%, however, for specimens that have the paste portion protected by entrained air. 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 it is subjected to five to seven cycles a day (Neithalath et al. 2005a).

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 under water (Yang et al. 2006). Addition of small dosages of fine aggregate or synthetic fiber has been reported to increase the freezing-and-thawing resistance (Wang et al. 2006).

5.8—Toughness

Synthetic fibers can be employed to increase toughness, defined as the energy absorption of concrete after cracking. Toughness can be quantified in one of several test methods, such as ASTM C1399. This test produces a postcracking 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 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).

5.9—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 as a means 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. 5.12 (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 Teflon sleeve, into which it fits snuggly. 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 α 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 select a proper pervious concrete thickness to minimize sounds of the desired frequency (800 to 1200 Hz is the most objectionable to the human ear).

CHAPTER 6—PERVIOUS CONCRETE MIXTURE PROPORTIONING

6.1—General

The process of developing mixture proportions for pervious concrete is often repeated trial-and-error efforts. 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, the overarching philosophy of mixture proportioning for pervious concrete is to achieve balance between voids, strength, paste content, and workability. Chapter 6 provides methods for trial batch proportioning of pervious concrete that is intended for use in pavements and other applications where drainage, percolation, or high porosity is needed. The results of the trial batch may have to be modified to better achieve the intended results in final production.

6.2—Materials

Pervious concrete is composed of cement or a combination of cement and pozzolan, coarse aggregate, and water. Although beyond the scope of Chapter 6, a small amount of fine aggregate may be incorporated to increase compressive strength. The most common gradings of coarse aggregate used in pervious concrete meet the requirements for ASTM C33/C33M aggregate sizes of 7 (1/2 in. to No. 4), 8 (3/8 in. to No. 8), 67 (3/4 in. to No. 4), and 89 (3/8 in. to No. 16).

Portland cement may conform to ASTM C150/C150M, C1157/C1157M, or any other specification that would

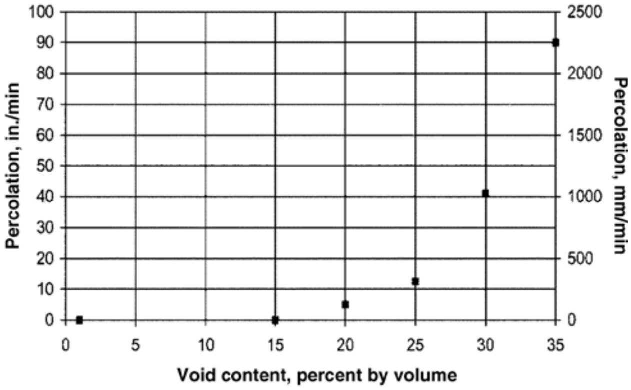

Fig. 6.1—Minimum void content for percolation on NAA-NRMCA tests and test method.

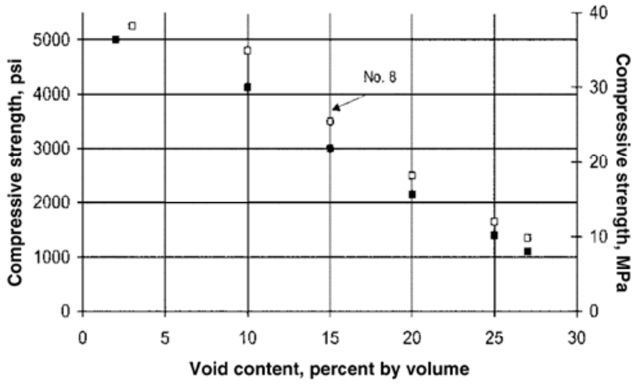

Fig. 6.2—Relationship between void content and 28-day compressive strength for No. 67 and No. 8 aggregate size.

produce an acceptable mixture. A combination of cementitious materials that each conform to the appropriate ASTM specifications can be used. Chemical admixtures are commonly used to improve various characteristics of pervious concrete. They should meet the appropriate ASTM specifications or other specifications that produce an acceptable mixture.

6.3—Water-cementitious material ratio

The water-cementitious material ratio (*w/cm*) is an important consideration for obtaining desired strength 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 good mixing and tend to cause balling in the mixer, prevent an even distribution of cement paste, and therefore reduce the ultimate strength and durability of the concrete. Experience has shown that *w/cm* in the range of 0.26 to 0.45 will provide the best aggregate coating and paste stability. The conventional *w/cm*-versus-compressive strength relationship for normal concrete does not apply to pervious concrete. Careful control of aggregate moisture and *w/cm* is important to produce consistent pervious concrete.

6.4—Void content

To ensure that water will percolate through pervious concrete, the void content, both in design of the mixture and measured as the percent air by ASTM C138/C138M (the gravimetric method) should be 15% or greater, as demonstrated in Fig. 6.1.

At a void content lower than 15%, there is no significant percolation through the concrete. It is believed that below 15% voids, there is not sufficient interconnectivity between the voids to allow for rapid percolation.

Figure 6.2 shows that the higher the void content, the higher the percolation rate, and the lower the compressive strength. The lower the void content, the lower the percolation rate, and the higher the compressive strength. This figure also shows the compressive strength increases as the nominal maximum-size aggregate decreases. Compressive strength of pervious concrete is 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 qualitative.

Table 6.1—Effective b/b_o values

	b/b_o	
Percent fine aggregates	ASTM C33/C33M Size No. 8	ASTM C33/C33M Size No. 67
0	0.99	0.99
10	0.93	0.93
20	0.85	0.86

6.5—Amount of coarse aggregate

Testing has shown that the dry-rodded density of coarse aggregate, as determined by ASTM C29/C29M, can be effectively used for proportioning pervious concrete (Meininger 1988). Those tests have shown that the ratio of the dry-rodded volume of coarse aggregate per solid volume of coarse aggregate b/b_o can be used as a design relationship, where

b/b_o = dry-rodded volume of coarse aggregate in a unit volume of concrete;

b = solid volume of coarse aggregate in a unit volume of concrete; and

b_o = solid volume of coarse aggregate in a unit volume of coarse aggregate.

The b/b_o value automatically compensates for the effects of different coarse aggregate particle shape, grading, and specific gravity. Furthermore, the b/b_o values for the nominal maximum-size aggregates typically used in pervious concrete, 3/8 to 3/4 in. (9.5 to 19 mm), are similar. Table 6.1 applies the b/b_o values for coarse aggregate sizes No. 8 and No. 67 with fine aggregate contents of 0, 10, and 20% of the total aggregate mass.

6.6—Paste volume, cement, and water contents

The proportioning of pervious concrete seeks to establish the minimum volume of paste necessary to bind the aggregate particles together, while maintaining the necessary void structure, strength, and workability. Figure 6.3 can be used

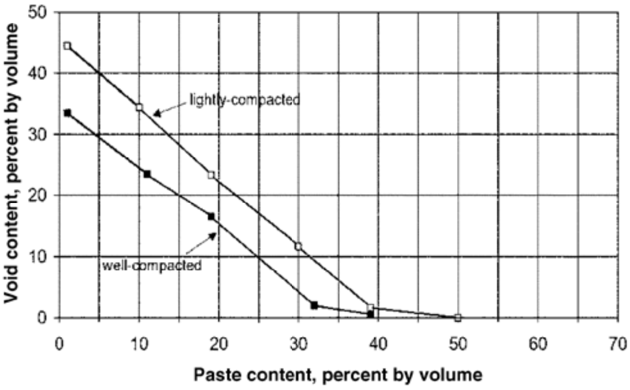

Fig. 6.3—Relationship between paste and void content for No. 8 aggregate size designations.

to estimate the volume of the paste for a mixture using normal weight No. 8 aggregates.

Once the paste volume is determined from Fig. 6.3, and the *w/cm* is selected, the cement and water quantities can be determined from the following absolute volume relationships:

$$\text{paste volume } V_P = \text{cement volume} + \text{water volume}$$
$$V_P = c/(3.15 \times 62.4 \text{ lb/ft}^3) + w/62.4 \text{ lb/ft}^3$$

Substituting $w = (w/cm)c$,

$$V_P = c/(3.15 \times 62.4 \text{ lb/ft}^3) + [(w/cm)c/62.4 \text{ lb/ft}^3]$$

c can be determined quickly by trial and error on spreadsheet or algebraically reduced to

$$c = [V_P/(0.315 + w/cm)] \times 62.4 \text{ lb/ft}^3 \qquad (6\text{-}1)$$

In SI units:

$$V_P = c/(3.15 \times 1000 \text{ kg/m}^3) + w/1000 \text{ kg/m}^3$$

Substituting $w = (w/cm)c$,

$$V_P = c/(3.15 \times 1000 \text{ kg/m}^3) + [(w/cm)c/1000 \text{ kg/m}^3]$$

c can be determined quickly by trial and error on spreadsheet or algebraically reduced to

$$c = [(V_P/(0.315 + w/cm)] \times 1000 \text{ kg/m}^3 \qquad (6\text{-}2)$$

Therefore, once the paste volume is determined from Fig. 6.3, and the *w/cm* is selected, the mass of cement can be calculated from Eq. (6-1). From the mass of cement, the water content can be computed. When fine aggregate is used, the paste volume should be reduced by 2% for each 10% fine aggregate of the total aggregate for well-compacted pervious concrete, and by 1% for each 10% fine aggregate of the total aggregate for lightly compacted pervious concrete. These reductions are necessary to maintain the same percent voids by volume.

6.7—Proportioning procedure

A procedure for producing initial trial batches for pervious concrete is shown in Section 6.7.1. The b/b_o method applies absolute volume concepts. Regardless of how the trial batch is derived, it is essential it be tested for the required fresh and hardened properties before being placed for its intended use.

6.7.1 b/b_0 *method*—The b/b_o method for designing a pervious concrete mixture can be broken-up into a series of eight steps:

1. Determine aggregate weight;
2. Adjust to SSD weight;
3. Determine paste volume;
4. Determine cementitious content;
5. Determine water content;
6. Determine solid volume;
7. Check void content; and
8. Iterative trial batching:
   a. Test for required properties; and
   b. Adjust mixture proportions until the required performance is achieved.

Example—Proportion a well-compacted pervious concrete mixture with a void content of at least 20%. The mixture should have a $w/cm = 0.38$. Use a No. 8 coarse aggregate having a dry-rodded density (unit weight) of 108.7 lb/ft^3, specific gravity of 2.75, and absorption of 1.2%. No fine aggregate will be used in the mixture.

Step 1: Determine aggregate weight

For No. 8 stone with no fine aggregate, Table 6.1 recommends b/b_o of 0.99, with dry-rodded density given as 108.7 lb/ft^3

$$W_a = 108.7 \text{ lb/ft}^3 \times 0.99 \times 27 \text{ ft}^3 = 2906 \text{ lb (dry)}$$

Step 2: Adjust to SSD weight

Given that the percentage absorbance of 1.2%

$$W_{ssd} = 2906 \text{ lb} \times 1.012 = 2941 \text{ lb (SSD)}$$

Step 3: Determine paste volume

Use Fig. 6.3 and read along the required percentage voids (20% for this example) to the well-compacted curve. Then read down to find the paste percentage at 15%. Fifteen percent of a cubic yard is 4.05 ft^3. Thus, $V_P = 4.05$ ft^3.

Step 4: Determine cement content

Applying Eq. (6-1),

$c = [V_P/(0.315 + w/cm)] \times 62.4 \text{ lb/ft}^3$

$c = [(4.05 \text{ lb})/(0.315 + 0.38)] \times 62.4 \text{ lb/ft}^3$

$c = 363$ lb

Step 5: Determine water content

$w = c(w/cm)$

$w = 363 \text{ lb}(0.38) = 138$ lb

Step 6: Determine solid volume

Aggregate volume $V_a = 2941/(2.75 \times 62.4) = 17.14 \text{ ft}^3$

Table 6.2—Typical* ranges of material proportions in pervious concrete†

	Proportions, lb/yd^3 (kg/m^3)
Cementitious materials	450 to 700 (270 to 415)
Aggregate	2000 to 2500 (1190 to 1480)
w/cm,‡ by mass	0.27 to 0.34
Aggregate:cement ratio,‡ by mass	4 to 4.5:1
Fine: coarse aggregate ratio,§ by mass	0 to 1:1

*These proportions are given for information only. Successful mixture design will depend on properties of the particular materials used and should be tested in trial batches to establish proper proportions and determine expected behavior. Concrete producers may have mixture proportions for pervious concrete optimized for performance with local materials. In such instances, those proportions are preferable.

†Chemical admixtures, particularly retarders and hydration stabilizers, are also used commonly, at dosages recommended by the manufacturer. Use of supplementary cementitious materials, such as fly ash and slag, is common as well.

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

§Addition of fine aggregate will decrease the void content and increase strength.

Cement volume $V_c = 363/(3.15 \times 62.4) = 1.84$ ft^3
Water volume $V_w = 138/62.4 = 2.21$ ft^3
Total solid volume $V_s = V_a + V_c + V_w = 17.14 + 1.84 + 2.21 = 21.19$ ft^3

Step 7: Determine percent voids

Percent voids = $(V_{tot} - V_s)/V_{tot} \times 100$
Percent voids = $(27.00 - 21.19)/(27.00) \times 100 = 21.52\%$

Step 8: Check estimated porosity

At 22% voids, Fig. 6.1 predicts a percolation rate of approximately 7 in./min (178 mm/min).

Step 9: Iterative trial batching and testing

The trial batch weights per cubic ft are as follows:
Cement = 362 lb
Water = 138 lb
No. 8 aggregate = 2941 lb (SSD)
Total weight = 3441 lb
Density = 3441/27 = 127.4 lb/ft^3

6.8—Typical ranges of materials

PerviousConcrete.org (http://www.perviouspavement.org/mixture%20proportioning.htm), a joint effort of National Ready Mixed Concrete Association (NRMCA) and the Portland Cement Association (PCA), has published Table 6.2.

CHAPTER 7—PERVIOUS PAVEMENT DESIGN

7.1—Introduction

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. This chapter discusses the aspects applicable to the structural design.

7.2—Structural design

7.2.1 *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 (Backstrom 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. ACI 330R provides typical stiffness values for 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, porous paving is designed to encourage water to saturate the subgrade below paving. This condition should be taken into account 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 level of compaction is typically 90% of Standard Proctor Maximum Dry Density (SPMDD). The modulus of subgrade reaction used in design should account for this lower level of compaction. 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 aforementioned 90% of the SPMDD or 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 not have any affect. 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 and subbase for permeability after compaction to confirm they still conform to both 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. Some permeability,

however, 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.

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. ACI 330R, Table 3.2, 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.

7.2.2 *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. As there are no standardized test methods for strength of pervious concrete, design and specification by concrete strength should be avoided.

7.2.3 *Structural thickness selection*—Sufficient performance data that offer a general standard pavement design for use in prolonged exposure to heavy truck traffic is unavailable. Success of existing pavements by installers around the country varies by experience, pavement and mixture designs, and local conditions.

Traffic categories are defined by average daily truck traffic (ADTT). ACI 330R provides 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.

Pavement designs with demonstrated performance history are available from experienced installers and being used currently in several areas of the U.S. Care should be taken to verify the installer has a history of successful performance both from installation quality and use of designs similar to any specific project needs. If unable to find suitable local installers with examples of successful projects, the National Ready Mixed Concrete Association (NRMCA) (2007) suggests pervious pavement sections of 6 in. (150 mm) of pervious concrete pavement for low (under 5) ADTT truck exposure in parking lots. This is based on historical success in the U.S. There are no current standard thicknesses for streets but there are examples of low-volume streets being installed with pavements ranging from 6 to 12 in. (150 to 300 mm) thick.

7.3—Stormwater management design

7.3.1 *General*—The major benefit of pervious concrete is its hydrological properties. From one state to another, local regulations determine how much of this benefit the designer is able to capitalize on. 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.

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 U.S., 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 distilled type condition because it is not practical, economical, or necessary. The intent is only to remove as much pollutant load as possible in an attempt to discharge cleaner water at sustainable rates, 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 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.

7.3.1.1 There are three specific design features of pervious concrete that the designer may benefit from: reduced runoff volume, reduced treatment volume, and reduced impervious area on the site.

7.3.1.1.1 *Reduced runoff volume*—Reduced runoff volume is the amount of stormwater that a piece of developed property would discharge to an adjacent land or water body if stormwater BMPs were not in place; this is 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 rentable space.

7.3.1.1.2 *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.

7.3.1.1.3 *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 building, sidewalk, and pavement areas. Many municipalities limit the amount of impervious area allowed on a given project site.

7.3.1.2 For a more thorough discussion of stormwater treatment BMPs, the reader is encouraged to review the

information at the EPA's Web site (http:// www.epa.gov/waterscience/stormwater). More information on local regulations can be found in the reader's regional stormwater management manual, such as the St. Johns River Water Management District's (SJRWMD) *Applicant's Handbooks: Regulation of Stormwater Management Systems* (1999). For general information on stormwater hydrology not linked to specific jurisdictions, review any of the stormwater textbooks, such as Ferguson's *Stormwater Infiltration* (1994), Ferguson's *Introduction to Stormwater: Concept, Purpose, Design* (1998), and Debo and Reese's *Municipal Stormwater Management* (2002).

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 7.1). The SJRWMD, for example, defines retention to include "pervious pavement with subgrade." The EPA defines pervious concrete as an infiltration system. Pervious concrete pavements can be designed to accommodate not only the rain falling on its surface, but also to capture a good portion of excess runoff from adjacent areas. To prevent premature clogging from runoff, the use of a sediment trap or other sediment separation system may be necessary. Also, calculate the increased water storage capacity requirements to hold the added storage load from the additional areas.

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.

7.3.2 *Pervious pavement maintenance*—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 assumptions 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. 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 preventative 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.

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 are used on this site to reduce pollution. Heavy vehicles prohibited. Do not resurface with nonpervious material. Call XXX-XXX-XXXX for more information."

Table 7.1—Pollutant removal of porous pavement (Winer 2000)

Pollutant	Pollutant removal, %*
TSS	95
TP	65
TN	82
NOx	NA
Metals	98 to 99
Bacteria	NA

*Data based on fewer than five data points.

Designers can account for the clogging potential of a 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). The designer of a pervious concrete pavement can reduce clogging potential by ensuring that the design of the site:

- Shows landscaped areas at lower elevations than the pervious concrete pavement (Fig. 7.1), 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;
- Minimizes soil erosion of disturbed areas. Bare soil in these areas should be avoided and the use of permanent pasture and brush cover is recommended. Special control measures, such as silt fences, should be used at all times during construction;
- Prevents vehicles from driving from unpaved areas onto the pervious concrete pavement;
- Does not lay in the path of wind from nearby unpaved or beachfront areas; 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:
    - The volume of water from the conventional pavement will be free of sediments;
    - The pervious subbase has been designed to handle the water from the combined areas; and
    - Sufficient pervious concrete surface area is available to catch leaves, litter, or other debris that may

Fig. 7.1—Example of landscaped area at lower elevations than pervious concrete pavement.

prematurely clog the pervious concrete between maintenance periods.

7.3.3 *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 rational 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. A well-maintained pervious pavement will typically drain faster than the subgrade soils, which limit the infiltration rate of the system. Some current research (Wimberley 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 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.

Research shows that as soil density increases, the rate of infiltration, and thus the permeability of the soil, decreases significantly (Das 1993). 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 overcompacted so as to reduce the permeability of the soils and increase the rational coefficient. The Florida Concrete and Products Association (FCPA) (1990) recommends compacting sandy subgrade soils to a minimum density of 92 to 96% of maximum dry density per AASHTO T-180

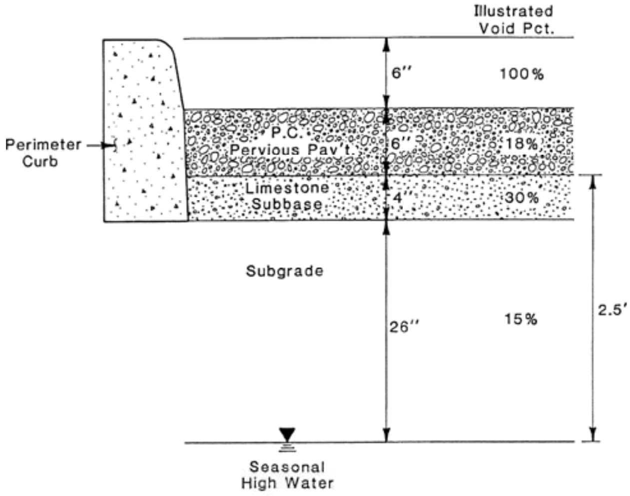

Fig. 7.2—Schematic of pervious concrete pavement designed as stormwater retention system (1 in. = 25.4 mm).

standards. In other parts of the U.S., 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 the 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 use, 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 and degree of compaction 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% effective 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 above the pavement surface in a curbed parking area (Fig. 7.2).

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 system average 66%. Additionally, there will be some direct recharge of the groundwater that will reduce the total runoff by as much as 33%. (Florida Department of Environmental Protection [FDEP]).

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:

- Placing a perforated pipe at the top of a crushed stone reservoir to pass excess flow after the reservoir is filled;
- Providing surface detention storage in a parking lot, adjacent swale, or detention pond with suitable overflow conveyance;
- Adding a sand layer and perforated pipe beneath a recharge bed for filtration of the water-quality volume; and
- 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 of the intricacies of a stormwater drainage design using pervious concrete pavement will be strongly tied to local practices and regulations. Refer to Section 7.3.5 for a sample set of design calculations that has been published by the FCPA (1990). Always review the full text and local stormwater regulations.

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.

7.3.4 *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%, and 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.

7.3.5 *Design example*—Given:

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

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

$$V_r = \text{rainfall (in.)} \times A \text{ (acre)} \times 43{,}560 \text{ (ft}^2\text{/acre)} \times 1 \text{ (ft)/12 (in.)} \quad (\text{ft}^3) \tag{7-1}$$

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

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

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

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

where V_r = volume of storage required, ft^3 (m^3); and A = size of the facility plus any contributing area, acre (m^2).

The Florida Concrete 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

$$V_p = A \times d_1 \times p_1/100 \quad (7\text{-}2)$$

$$V_s = A \times d_2 \times p_2/100 \quad (7\text{-}3)$$

where V_p = available storage in pavement, ft^3 (m^3); V_s = available storage in subgrade, ft^3 (m^3); A = area of the pavement, acre (m^2); d_1 = thickness of the pavement, ft (m); d_2 = thickness of the subgrade, ft (m); p_1 = percentage of void space in the pavement (%); and p_2 = percentage of void space in the subgrade (%).

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 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 FCPA guide (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 the Atlanta Regional Commission's (ARC's) *Georgia Stormwater Management Manual* (2001).

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.

7.4—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 or 10 in. (200 or 250 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, below the effect of the compaction, had a consistent 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 void ratio 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.

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. A sample specification is available from ACI 522.1. Construction starts with thorough planning. A preconstruction conference and/or construction of test sections are recommended to address issues such as:

- Confirming that all project personnel are working from the latest set of plans and specifications, and all revisions are documented;
- Verifying that all required documents and submittals have been completed;
- Determining the construction sequence and joint spacing;
- Arranging the staging area for equipment, material, jobsite trailers, personnel needs, and safety requirements;

- Arranging adequate access for concrete delivery trucks and concrete conveying systems;
- Selecting the optimum equipment for project size and anticipated conditions;
- Coordinating on-site inspections, and/or materials testing;
- Verifying the proposed mixture design, material and admixture availability, and proposed delivery schedule with the concrete supplier; and
- Verifying that the pervious concrete contractor, concrete plant personnel, and testing personnel (Section 9.3) are adequately qualified.

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 2005a). The process is depositing, screeding, compacting, and following immediately with sheet membrane curing. Equipment that has been used successfully to place pervious concrete includes low-frequency vibrating truss screeds in combination with heavy pipe rollers, both single- and double-tube counter rotating tube screeds, plate compactors, slipforms, laser screeds, and machines specifically made for placing pervious concrete. Normal concrete finishing procedures are not employed.

No matter what equipment is used, a pervious pavement cannot be successfully constructed unless the concrete placed has the correct consistency. If too dry, a concrete creates issues with cohesiveness and cement hydration efficiency, while too wet a mixture results in the paste phase draining down, leaving a weak structure and possibly clogging the pavement bottom. Admixtures such as hydration stabilizers, viscosity modifiers, and water reducers 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 sheet membrane curing can be in place within 20 minutes of concrete placement, although this time may be significantly reduced depending on environmental conditions. 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.

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 in an area where freezing and thawing is a concern, then a base of gravel may not be required. The project engineer should make this determination based on local regulations, soil permeability, stormwater volume, anticipated traffic loads, and pavement purpose.

When the subgrade soil properties require that a rock base be placed below the pavement as a stormwater storage basin, nonwoven, geotextile fabric should be placed between the layer of rock and prepared subgrade. Fabric allows water to pass through, but keeps the soil in the subgrade from eroding or migrating into the voids of the subbase layer.

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. Failure to provide a moist support layer may result in a reduction in pavement strength and could lead to premature pavement failure. To provide a level surface for pavement construction, wheel ruts should be raked and recompacted before concrete placement begins.

8.3—Placing

A well-planned project 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 before construction begins. Locations of fixed objects should be established with the joint pattern and construction methods in mind.

Pervious concrete placement should be completed as quickly as possible. Pervious concrete has almost no excess water in the mixture. Fresh material exposed to the elements for a significant time period will lose water needed for hydration as well as retention of the cohesiveness of the mixture. This 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, and scheduled for rapid placement and immediate curing of the pavement.

8.3.1 *Forms*—Typical pervious pavement construction requires the use of edge forms, as is typical for cast-in-place slab-on-ground construction. Forms may be made of wood, plastic, or steel and should be as thick as the pavement. 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 recommendations. 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. 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 done by direct discharge from the chute of the mixer truck directly onto the subgrade or subbase (Fig. 8.1). Generally only one section of chute can be added to the chute section mounted on the mixer truck. This limits the width of placement lanes to 15 ft (4.5 m). For placements that mixers cannot reach, or where the soil disturbance is to be minimized, a conveyor may be used (Fig. 8.2). After the concrete is deposited, it should be cut to a rough elevation with a concrete rake or similar hand tool (Fig. 8.3). Care should be

Fig. 8.1—Placement of pervious concrete by rear-discharge mixer truck.

Fig. 8.2—Use of conveyor to place pervious concrete.

Fig. 8.3—Raking pervious concrete to rough elevation.

taken to minimize filling voids in the concrete by overvibration or walking in the plastic concrete and contaminating the pervious concrete with deleterious material.

8.3.3 *Riser strips*—Pervious concrete is compacted into its final position, therefore, riser strips may be placed on top of the forms to provide an initial strikeoff elevation (Fig. 8.4). These strips vary from 3/8 to 3/4 in. (9 to 19 mm) thickness; the necessary thickness will be dependent on the required surface compaction, thickness of the pavement section, the

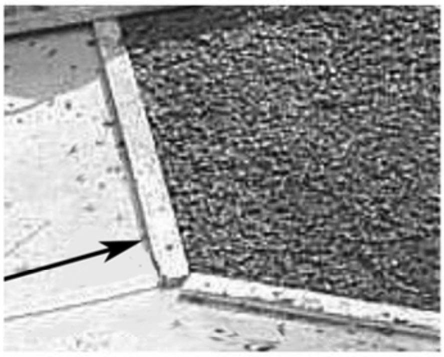

Fig. 8.4—Example of riser strip in place.

Fig. 8.5—Use of vibratory screed for strikeoff of pervious concrete.

aggregate used in the pervious 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. For small jobs such as driveways, or for tight areas, a hand-held straightedge or vibrating screed is acceptable. For larger jobs, an A-frame, low-frequency, vibrating screed may be used (Fig. 8.5). It is important to strike off the concrete as quickly as possible. Handwork for larger placements, therefore, is not recommended due to its lack of speed. Weighted spinning-tube screeds followed by cross rolling have been used successfully to place and compact the pavement in one step, eliminating some need for riser strips. When using this process, the mixture should be properly proportioned and the concrete placed at a relatively fluid consistency to achieve adequate compaction.

There have been limited projects where laser screeds 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 whichever method of compaction and finishing used, 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

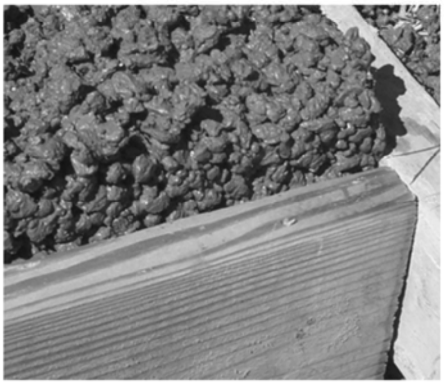

Fig. 8.6—Result of riser strip use after removal.

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.

8.3.6 *Using pavement as a form*—Special care should be taken when placing a pervious concrete section next to an earlier placement 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 covering the earlier placement to reveal just the edge of the pavement. Care should be taken to keep as much of the previous placement covered as possible. Misting of the uncovered areas is recommended;
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;
4. Strikeoff the freshly placed pervious concrete to the proper elevation and compact edges, being careful not to impact the existing placement;
5. Continue with roller-finish as usual, lineup joints with previous placement; and
6. Re-cover the existing placement and the new placement with curing-sheeting.

8.4—Consolidation

When using riser-strips, they should be removed from each form immediately after strikeoff (Fig. 8.6) and the concrete be compacted to the elevation of the form with a weighted roller (Fig. 8.7). A hand-tamp may be used along the edges to facilitate compaction along the forms. The roller compacts the near-surface aggregates, resulting in a stronger bond between the surface aggregates but decreasing the permeability of the surface. The construction process should result in both adequate strength and permeability. The roller should span from form to form and be heavy enough to obtain the necessary compaction. The average roller of the size needed to span a 12 ft (3.7 m) lane width weighs approximately 500 lb (227 kg). A custom-built rolling tool (Fig. 8.8) can be used in tight areas and for smaller placements. The roller in Fig. 8.8 weighs approximately 70 lb (32 kg). To decrease the chance of leaving roller-marks in the surface of the pavement, small rollers should have machined beveled-edges.

Fig. 8.7—Example of compaction of pervious concrete by rolling.

Fig. 8.8—Example of small roller used for compacting small paved area.

Extra compaction may be necessary in some areas such as tight turn-radiuses of the parking lot pavements. Because these areas may receive more wear from increased stresses as a result of the turning motion of passing vehicles, it is recommended these areas receive a greater surface compaction, even at the loss of some surface permeability, by using a thicker riser-strip in the radius areas

Some situations require extra effort to ensure a quality pavement. Where ride quality is of special concern, as in drive-lanes, the pavement may be cross-rolled to smooth out vertical deviations (Fig. 8.9). Adjacent to sidewalks and at exposed pavement edges, the concrete may be tooled to provide a smoother and tighter corner (Fig. 8.10). This operation performed at the wrong time could result in cracking of the matrix and thus increased raveling. Great care should be taken when performing this operation. After strikeoff, compaction, and edging, no other finishing operations should be performed.

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 1/3 to 1/4 of the thickness of the pavement. Although it is highly recommended that joints be installed in the fresh concrete with special tools, saw cutting joints after the concrete hardens can also be performed. Shrinkage cracks will occur in pervious concrete as well as in conventional

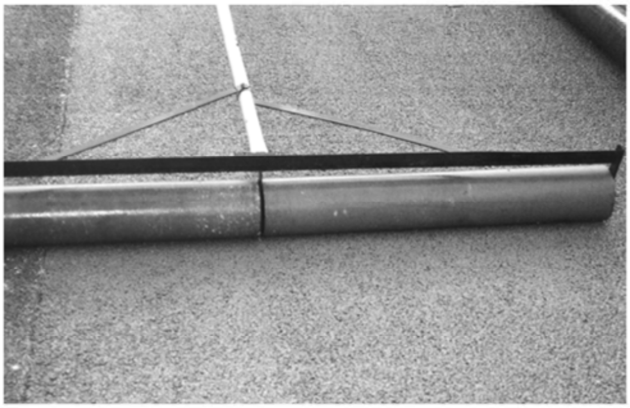

Fig. 8.9—Secondary roller used for cross-rolling pervious concrete to improve the ride quality of pavement.

Fig. 8.10—Edging pervious concrete to improve appearance of corners.

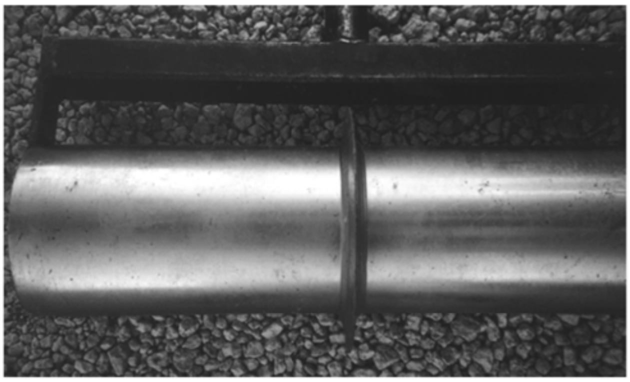

Fig. 8.11—Detailed view of jointing tool for pervious concrete.

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. A specially designed compacting roller-jointer with a blade that is at least 1/4 the thickness of the slab, and with enough mass to force the blade to cleanly cut the joint, is the tool of choice (Fig. 8.11). In placements with wide lane widths, a longitudinal joint

Fig. 8.12—Example of jointing tool built into primary roller.

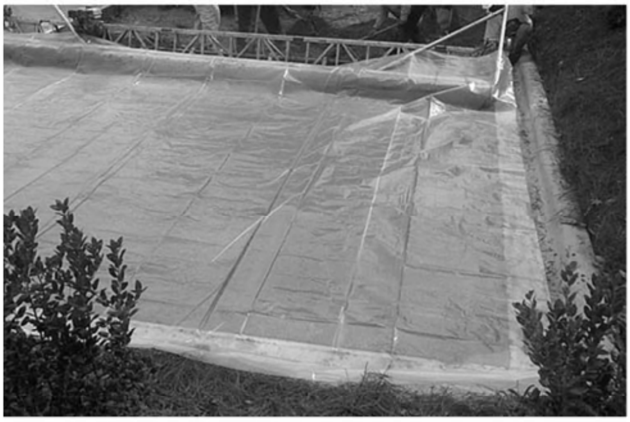

Fig. 8.13—Demonstration of curing with plastic sheeting immediately after compaction

may be cut with the compacting roller (Fig. 8.12). In all types of roller-jointers, the junction of the blade and roller should incorporate a small concave-radius to reduce the square-edges at the top of the joint. Square edges have a greater tendency to ravel under traffic loading.

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 enough polyethylene cover material to saw cut the required areas should be removed (Fig. 8.13). After sawing, the exposed areas should be soaked with water, which flushes the pores of the fines generated by sawing and ensure that sufficient water is present for proper curing. Immediately re-cover the exposed area with a polyethylene covering sheet as soon as saw cuts have been made.

8.6—Curing and protection

The open pore structure of pervious concrete makes curing particularly important because of the larger surface area exposed to drying (dehydration). 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. The cover material should be heavy-duty polyethylene sheet, meeting the requirements of ASTM C171, of sufficient dimension to cover the entire width of a lane (Fig. 8.13). Woven materials

Fig. 8.14—Example of use of reinforcing bars to hold down curing material.

such as burlap and geotextile fabric should not be used as they will not hold the moisture in the concrete. Spray-applied curing compounds do not produce acceptable results.

Strikeoff, compaction, and curing operations should be kept as close together as possible to prevent the top surface of the pervious concrete from drying. Following the placement process, as soon as the strikeoff operation has moved on to a new riser strip, the used riser strips should be removed and the compaction operations begun. 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 following strikeoff operations and before compaction. Before covering, if the concrete has lost its sheen, it should be lightly misted with water but never sprayed.

The polyethylene cover should completely cover all exposed surfaces and should be secured in place outside all pavement edges and at laps to prevent evaporation from the concrete and being displaced by wind (Fig. 8.14). Reinforcing bars, lumber, or concrete blocks may be used to secure the polyethylene cover to prevent it from being blown off. Dirt, sand, or other granular material 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. Over time the discoloration should even out to a single gray color.

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. Striping should be applied only after the curing period has passed (Fig. 8.15). No traffic should be allowed on the pavement during curing. The general contractor should take measures to prevent damage to the pavement due to abuse from construction operations. Specifically, the general contractor should prohibit removal of the curing material and prevent any traffic on the pervious concrete pavement. Additionally, the general contractor should not allow storage of building and landscaping materials on the pavement surface as these materials can clog the pores or otherwise damage pervious pavements.

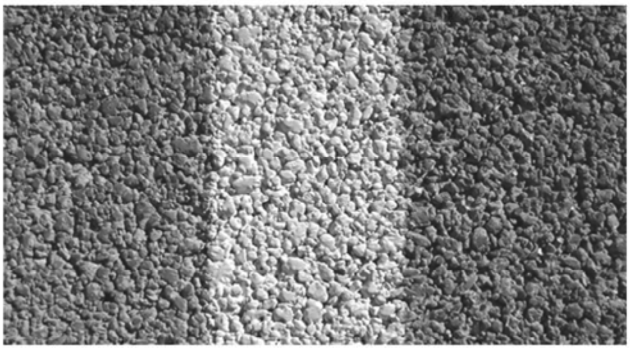

Fig. 8.15—Painted lines visible on pervious concrete pavements.

8.7—Cold weather protection

Pervious concrete is more sensitive to cold weather than normal concrete (Section 8.1) and, therefore, pervious concrete construction may be suspended or curing blankets used when ambient temperature during, and one day after, placement is expected to fall below 40°F (4°C). Due to rapid evaporation causing insufficient water for cement hydration, hot water should not be used in batching pervious concrete. 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 to serve this purpose.

8.8—Hot weather protection

In hot weather, transporting, placing, and compacting should be done as quickly as possible. An evaporation retardant may be applied to the surface of the concrete following the strikeoff process to retard the loss of moisture on the surface. After consolidation and before placing the polyethylene, the surface may be lightly misted with water or an evaporation retardant if the surface appears to be losing its sheen appearance.

8.9—Repairing pervious concrete pavements

8.9.1 *Grinding*—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.

Table 8.1—Typical maintenance activities for pervious concrete placement

Activity	Schedule
• Ensure that paving area is clean of debris • Ensure that the area is clean of sediments	Monthly
• Seed bare upland areas • Vacuum sweep to keep the surface free of sediment	As needed
• Inspect the surface for deterioration or spalling	Annually

8.9.2 *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.

8.9.3 *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.

8.10—Maintenance

Pervious concrete pavements are infiltration-based systems. Water passing through the pavement will carry with it varying degrees of soluble and insoluble pollutants and trash. 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. Two commonly accepted maintenance methods are pressure washing and power vacuuming. Pressure washing may force some of the debris down through the pavement surface. This is effective, but care should be taken not to use too much pressure, as this will damage the pervious concrete. 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 suggested maintenance schedule is found in Table 8.1.

Research conducted by the FCPA (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.

CHAPTER 9—QUALITY CONTROL 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 of the subgrade condition are to ensure adequate density, support value, and permeability. Testing of the pervious concrete mixture should be conducted for both the fresh and hardened properties of the concrete for quality assurance of density and thickness. 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.

Due to the lack of test methods for this material, ASTM Subcommittee C09.49 is developing test methods specifically for pervious concrete. As of 2008, five test standards were in development, including: Fresh Density and Void Content, Compressive Strength, Flexural Strength, Field Permeability, and Hardened Density and Porosity.

9.2—Preconstruction inspection and testing

Determining the permeability of the subgrade and soil analysis 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), soil testing and classification (ASTM D2487), and standard or modified proctor test (ASTM D698 or ASTM D1557). The results of these tests will provide the designer with the necessary data.

The standard percolation test used for designing septic fields is not an appropriate test for determining subgrade permeability for pervious pavements. A test section of the subgrade should be compacted to the specified density as part of the soil analysis before completion of the project design. 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 local soils.

Normal soil testing procedures for subgrade density (compaction) in accordance with a standard ASTM test procedure should be performed before concrete placement as part of a normal quality-control plan.

9.3—Inspection and testing during construction

As described in ACI 522.1, acceptance criteria should have two distinct aspects. The first criterion should be based on the pervious concrete mixture as delivered and is based on the density. For each day's placement, or when visual inspection indicates a change in appearance of the fresh mixture, at least one test should be conducted to verify the density of the material. The test of the mixture should be conducted in accordance with ASTM C1688/C1688M. Acceptance should be based on ±5 lb/ft^3 (80 kg/m^3) of the specified fresh density. The second acceptance criterion should be based on the completed pavement as outlined in the following section. Field tests and inspections of pervious concrete should be performed by an individual certified as

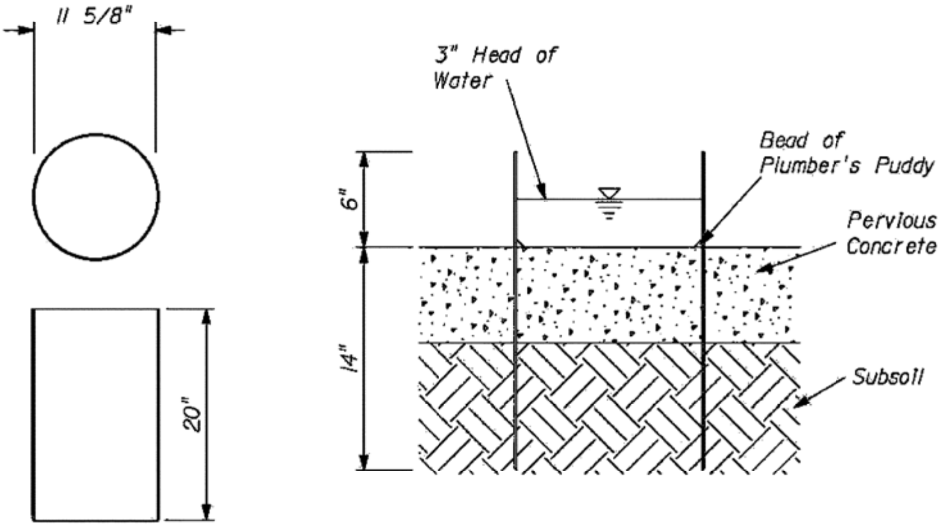

Fig. 9.1—Single-ring infiltrometer (1 in. = 25.4 mm).

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

The hardened density of a properly placed pervious pavement should not vary substantially from the fresh density of the mixture. Coring of three samples of the pavement will result in acceptance samples for thickness and density and should be tested for each lot of 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. The cores should be measured for thickness by an ACI certified Laboratory Technician according to ASTM C42/C42M and tested for density according to ASTM C140 (ASTM Subcommittee C09.49 is developing methods specifically for Pervious Concrete.). The placement thickness should be determined using untrimmed, hardened core samples. After thickness determination, the cores should be trimmed and measured for unit weight in the saturated condition as described in Paragraph 9.3, Saturation, of ASTM C140.

After immersing the trimmed cores in water for 24 hours, drain for 1 minute, remove surface water with a damp cloth, and then weigh immediately. Tolerance for thickness reported as the average of three cores of each lot should not be more than 1/4 in. (6 mm) less than the specified thickness, with no single core exceeding 1/2 in. (13 mm) less than the specified thickness, nor should the average compacted thickness be more than 1.5 in. (40 mm) more than the specified thickness. The acceptable hardened density should be within ±5% of the approved hardened density from the test panels.

In addition, visual inspection of the cores will allow for verification of the necessary open void space to facilitate drainage. A visual inspection that shows a fully closed or severely restricted pore structure may indicate a pavement that will not function properly, and those sections demonstrated to be essentially impervious should be removed and replaced. Agreement as to what is essentially impervious and the method of measurement should be achieved before initial placement.

Tests are being developed for determining the in-place permeability of pavements. One of the recent test methods that have been developed is the embedded single-ring infiltrometer (Fig. 9.1) to determine the infiltration rates of the pervious concrete system (Wanielista et al. 2005). This can be used either as a preconstruction tool or a postconstruction tool. The single-ring infiltrometer uses the same testing procedure as the double ring, as outlined in ASTM D3385 with the modification of its embedment and the use of a single ring. It is postulated that this is a valid modification to test the infiltration rates of the entire system and avoid a lateral migration of water in the pavement alone. The depth of penetration is an important variable and will be refined based on results from extensive field testing.

At no time should acceptance be based on the compressive strength of the pervious concrete, either as delivered or as cored from the pavement. Due to the relationship between compaction and compressive strength, there is a wide range of strengths that can be generated from a single delivery of pervious concrete. Additionally, there are no standard test methods 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 testing results may be inaccurately low. Local experience with materials through completed projects, test panels, or both should give an indication whether a specific mixture proportion will have sufficient strength to withstand the stresses of the design traffic loads.

CHAPTER 10—PERFORMANCE

10.1—General

Pervious concrete pavements more than 30 years old are still in service. Information from controlled studies is available concerning the long-term performance of pervious concrete pavements. The performance parameters discussed in Chapter 10 include changes in infiltration rates, structural distress, surface distress, and resistance to freezing and thawing.

10.2—Changes in infiltration rates

Clogging occurs when foreign materials restrict the ability of water to flow through the pervious concrete pavements. These foreign 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 are water-borne, wind-borne, or tracked onto the pervious concrete pavement by traffic. Vegetative matter comes from trees or plants adjacent to the pervious concrete pavement.

Water-borne fines come from stormwater runoff that starts outside the limits of the pervious concrete pavement and transports material onto the pavement. A geometric design of the pervious concrete pavement that does not allow stormwater or traffic to introduce 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 properly designed, constructed, and maintained pervious concrete pavements showed only small amounts of clogging after many years of service. The study also included the percolation rate measurement on clogged pervious concrete pavement. The percolation rate of the clogged pervious concrete pavement was still equal to adjacent grass. A more recent investigation of several field sites in Florida and other southeast U.S. locations has been carried out (Wanielista et al. 2007). This study indicated that pervious concrete pavements that were installed 10 to 15 years ago, with no maintenance requirements, are operating in a satisfactory manner with insignificant amounts of clogging. This study also looked at potential rejuvenation methods in case clogging occurred, which included pressure washing and/or vacuum sweeping of the pavement. It also concluded that the most important criteria for continued satisfactory performance of these pavements were proper design and installation.

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 can cause surface raveling.

10.4—Surface distress

Surface distress is the removal of loose aggregate material from the pervious pavement surface. 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 stops. A modified version of an abrasion test to assess a mixture's resistance to surface distress has been developed (Offenberg and Davy 2008).

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 it to an underlying drainage layer and soil, and will not be retained in its 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. 2005a). It is possible to add air-entraining admixture to pervious concrete mixtures to protect the coating paste, but the entrainment of air cannot be verified or quantified by current standard test methods. Pervious concrete that is partially saturated could possibly have sufficient voids for water movement, demonstrating good freezing-and-thawing resistance.

ASTM C666/C666M is used to test fully saturated concrete samples. This 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. Currently, there is no standard method for evaluating the resistance to freezing and thawing of pervious concrete. The important factor is its ability to drain any water entering its structure in the anticipated weather conditions.

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 pounds of cement per cubic yard (338 kg/m^3), 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%. They determined 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.

These precautions are recommended to enhance the freezing-and-thawing resistance of pervious concrete:

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

- Attempt to protect the paste by incorporating air-entraining admixture 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;
- Place perforated PVC pipe in the aggregate base if the aggregate subbase is not thick enough to drain water through the paving, to capture the water and let it drain away below the pavement; and
- Consider adding a small amount of sand to the concrete mixture.

Not every situation warrants all of these safeguards. The safeguards are organized in the order of preference. For example, a pervious concrete sidewalk at Pennsylvania State University in University Park, PA, which is a hard, wet-freeze area, has shown good performance over five winters and has only an 8 in. (200 mm) thick layer of aggregate base underneath the pervious concrete. There are many pervious concrete projects in Georgia, Pennsylvania, Tennessee, North Carolina, and New Mexico 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 a number of 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 ground-water table rises to a level less than 3 ft (0.9 m) from the top of the surface of the subgrade. New details, however, have been developed for using pervious concrete on sites with high groundwater tables and poorly draining soils (Ohio Concrete Ready Mixed Association) (http://www.ohioconcrete.org).

CHAPTER 11—LIMITATIONS, POTENTIAL APPLICATIONS, AND RESEARCH NEEDS

11.1—Pervious concrete in cold climates

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:

- Strength determination and limitations;
- Characterization of material structure;
- Freezing-and-thawing and cold climate applications;
- Porous grout and other pore pressure reduction potentials;
- Stormwater management;
- Environmental filtering/remediation potential;
- Surface deterioration and repair;
- Development and standardization of broader testing methods;
- Nondestructive test methods for performance evaluation and prediction;
- Urban heat island effect, carbonation, and other thermal properties; and
- Other novel applications.

11.2—Strength determinations and limitations

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; Wimberley 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). ASTM C39/C39M has therefore not proven to be an effective means of measuring compressive strength. 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 U.S., 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 pavement in the world is a section of roadway in the Netherlands comprised 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.

More research is also needed into the fatigue performance of pervious concrete under load because that influences pavement design. Preliminary research shows that pervious concrete has the same fatigue performance as plain concrete, but that work needs to be expanded (Tamai et al. 2004).

11.3—Characterization of the material structure

The properties and performance of any porous material depends extensively on its 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 features 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.

11.4—Freezing-and-thawing and cold climate applications

More research would be valuable to evaluate the efficacy 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 be conclusively answered so that 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 deicing salts 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 preventative 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 (FCPA 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).

Field performance was investigated for approximately two dozen pervious concrete sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. In addition to field observations and nondestructive testing, laboratory testing was performed on cores removed from some of the test sites. The installations evaluated had generally 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).

11.5—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 and reported by the Bechtel Corporation in 1995. The studies encompassed a wide range of pumped materials that had drainage properties. Several mixture proportions were developed and are in the testing phase (Yen et al. 2002).

11.6—Stormwater management

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; Wimberley 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. 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. 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:

- 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;
- There may not be a first flush if pollutants are not easily washed away or dissolved; and
- 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. 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 and cleaning of the catch basin after removing 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:

- Greases and low volatile content oils occurring routinely on parking areas, such as oil drips from vehicles, will probably be adsorbed onto the surface of the pervious concrete 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 was 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;

- 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; and
- 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 much 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.

11.7—Environmental filtering/remediation potential

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.

11.8—Surface deterioration and repair

As with any other pavement surface, especially those under heavy vehicle loads, there is expected to be aging and deterioration of the pervious concrete surface over time. Offenberg and Davy (2008) proposed a test method for determining the raveling potential of a pervious concrete mixture. This method uses a 4 in. (100 mm) tall, 4 in. (100 mm) diameter cylindrical specimen that has only been cured for 7 days. The specimen is tumbled in an apparatus typically used for ASTM C131. The raveling potential relates to the difference in specimen mass before and after testing. Further research is needed to quantify a mixture's potential for surface deterioration after field application and service, and to correlate this back to fresh properties.

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. 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.

11.9—Development and standardization of broader testing methods

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. The most frequently cited variable that is tested on pervious concrete is porosity. There are, however, many different definitions for porosity (effective porosity, total porosity, drained porosity, void content) that are not well defined and are equally important, depending on the application and design need of the pervious system. A variety of porosity measurement techniques have been investigated on pervious concretes (Crouch et al. 2003; Neithalath 2004; Marolf et al. 2004; Neithalath et al. 2006; Montes et al. 2005). Standardization or referencing to these techniques is crucial for comparison of most characteristics and for design criteria of pervious concrete systems.

Field quality control and assurance tests need to be established. Methods for testing workability or consistency, like the slump test for plain concrete, are necessary quality control tools for the concrete producer, as are tests for compressive strength and air entrainment. Owner's quality assurance tests for strength and durability are significant needs for pervious concrete pavements.

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. For instance, field infiltration rate methods similar to those for other porous media are needed. In addition, pollutant removal testing methods would be beneficial to design and specify pervious concrete for its potential water quality benefits.

11.10—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 the 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 predict the permeability of pervious concrete fairly accurately (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 void ratio.

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

Conventional, dark pavement surfaces are considered to be 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 considered to be 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. There is some current research, however, into the absorption of carbon dioxide 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 our atmosphere can be better understood.

11.12—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.

Pervious concrete is sometimes referred to as EPC and has been shown to have some benefits in sound absorption. Some applications are as road surfaces and sound barriers (Neithalath et al. 2005b; Tamai et al. 2004). A number of European studies relating to sound absorption characteristics of pervious concrete are available and so are a few studies carried out in the U.S. (Neithalath 2004).

CHAPTER 12—THE ENVIRONMENT AND PERVIOUS CONCRETE

Pervious concrete is a unique and innovative means of managing stormwater (Fig. 12.1). From an environmental perspective, among its primary benefits is the reduction in the total volume of runoff that otherwise carries substantial amounts of pollutants into our local streams, rivers, lakes, and oceans. Costly infrastructure is committed to dealing with the sheer volume of stormwater and the ability to effectively remove significant amounts of pollutants is increasingly challenging. By infiltrating the stormwater—a recommended best management practice of the U.S. EPA for dealing with runoff—not only is the volume of stormwater greatly reduced but pervious concrete effectively provides "first flush pollution mitigation" where approximately 90% of the pollutants are carried away in the first 1.5 in. (38 mm) of typical significant rain events. The filtration provided by the voided matrix within pervious concrete retains at least 80% of the organic pollutants, and naturally occurring microbial growth provides further treatment before the few pollutants that remain are eventually converted by native soils.

The infiltration provided by pervious concrete recharges groundwater, provides irrigation to nearby surface vegetation and tree root systems, and mitigates "thermal pollution" where otherwise runoff significantly contributes 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. Pervious concrete also absorbs and retains less heat and requires less night illumination than the most commonly used conventional pavement, giving it the potential to positively impact urban heat island mitigation and carbon footprint through energy reduction.

Fig. 12.1—Pervious concrete stormwater management system.

12.1—Pervious concrete and the LEED® green building rating system

When pervious concrete is used in building site design, it can aid in the process of qualifying for numerous credits in the LEED green building rating system (Version 2.2) as administered by the U.S. Green Building Council. With rapid changes in the LEED system and pervious concrete technology, the most current information about this topic can be found in the ACI Concrete Knowledge Center at http://www.concrete.org/tkc/knowledge_center.htm.

LEED provides a framework for evaluating building and site performance, meeting sustainability goals through five credit categories: sustainable site development, water savings, energy efficiency, materials selection, and indoor environmental quality. Note, however, that LEED points are not gained directly by the use of a product but by meeting a specific sustainability goal of the rating program. Pervious concrete can contribute to many LEED categories including: Sustainable Sites, Water Efficiency, Materials and Resources, and Innovation in Design (RMC Research Foundation 2006; Ashley 2008).

Specific credits where pervious concrete can aid the designer include:

12.1.1 *LEED Credit SS-C6.1 Stormwater Design: Quantity Control, and LEED Credit SS-C6.2 Stormwater Design: Quantity Control*—The intent of these credits is to limit disruption and pollution of natural water flows by managing stormwater runoff, increasing on-site infiltration and eliminating contaminants. Pervious concrete can contribute to this credit by reducing stormwater flow, allowing water to soak through and infiltrate to the ground below. Pervious concrete can also reduce the pollutant loads by filtering contaminants as the water is transferred through the pavement. On building sites where the existing imperviousness is greater then 50%, Credit SS-C6.1 requires reducing the rate and quantity of stormwater runoff by 25% from the 2-year, 24-hour design storm. On building sites where the existing imperviousness is less than 50%, the requirement specifies that the post-development peak discharge rate and quantity from the site should not exceed the pre-development peak rate and quantity. Generally, by incorporating a pervious concrete pavement system on site, the project can meet these criteria and thus obtain the LEED points for these credits.

12.1.2 *LEED Credit SS-C7.1 Heat Island Effect: Non-Roof*—The intent of this credit is to reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impact on microclimate and human and wildlife habitat. This credit requires any combination of the following for 50% of the site hardscape (sidewalks, parking lots, drives and access roads), shade within 5 years of occupancy, paving materials with a solar reflectance index of at least 29, or/and an open grid paving system. A second method to achieve this credit includes providing under-cover parking areas for 50% of the parking spaces. Pervious concrete acts to reduce the heat island effect of concrete by absorbing less heat from solar radiation than darker pavements. The relatively open pore structure and the light color of pervious concrete stores less heat, therefore reducing the heat reflected back into the environment and helping to lower heat island effects in urban areas. The heat island effect can be further minimized by the addition of trees planted in or around parking lots. Trees offer shade and produce a cooling effect for the pavement. Pervious concrete pavement is ideal for protecting trees in a paved environment (many plants have difficulty growing in areas covered by impervious pavements, sidewalks, and landscaping because air and water have difficulty getting to the roots). Pervious concrete pavements or sidewalks allow adjacent trees to receive more air and water and still permit full use of the pervious concrete pavement.

Pervious concrete has not been explicitly approved for use in SS 7.1 for its high albedo properties; however, the pervious concrete design may be submitted for interpretation. If the concrete producer has reflectance test results for the pervious concrete mixture used on the project, he or she may choose to submit a letter to the contractor (and architect) indicating the results of the tests, increasing the chance that the SS 7.1 credit will be awarded.

As a generalization, a concrete producer can increase the solar reflectance of concrete through materials selection. As portland cements can vary in color, a lighter-colored cement could improve the solar reflectance of a pervious concrete mixture as well could the introduction of integral coloring (white) and the potential use of a supplementary cementitious material such as slag (usually noticeably lighter than conventional plain gray cement). The size, shape, gradation, and color of the aggregates could affect the amount of "open gradedness," which contributes to the lack of comparative albedo in pervious concrete. The technique and type of equipment a contractor uses for placing the concrete could also contribute to this. As test sections are highly recommended for most critical applications of pervious concrete, doing such early enough to allow for in-place specimens to be evaluated for solar reflectance index (SRI) prior to placement and potentially prequalified, may be a practical means of acceptance.

12.1.3 *LEED Credit WE C1.1 Water Efficient Landscaping*—The intent of this credit is to limit or eliminate the use of potable water, or other natural surface or subsurface water resources available on or near the project site, for landscape irrigation. To earn this credit, potable water for irrigation should be reduced by 50% when compared to a midsummer baseline case. The granular subbase (retention layer) under pervious concrete can be used to store stormwater for irrigation, helping to satisfy this credit. If no irrigation is required for a project, two points may be earned.

12.1.4 *LEED Credits MR-C4.1 AND MR-C4.2 Recycled Content*—The intent of this credit is to increase the demand for building products that have incorporated recycled content material reducing the impacts resulting from the extraction of new material. The requirements for these credits are the use of materials with recycled content such that the sum of post-consumer recycled content plus 1/2 of the pre-consumer recycled content constitutes at least 10% or 20% (based on the dollar value of the material), respectively, of the total value of materials in the project. Most concrete

Fig. 12.2—Supplementary cementitious materials. From left to right: fly ash (Class C); metakaolin (calcined clay); silica fume; fly ash (Class F); slag; and calcined shale.

Fig. 12.3—Pervious concrete parking lot.

contains recycled materials in the form of supplementary cementitious materials (SCMs) such as fly ash, slag, or silica fume (Fig. 12.2). The use of SCMs or recycled aggregate in pervious concrete or base material contributes to recycled content needed for this credit. Supplementary cementitious materials are considered pre-consumer recycled material, and recycled aggregates from a demolished project are considered post-consumer recycled material.

12.1.5 *LEED Credit MR-C5.1 AND MR-C5.2 Regional Materials*—The intent of this credit is to increase demand for building products that are extracted and manufactured locally, thereby reducing the environmental impacts resulting from their transportation and supporting the local economy. To meet the intent of this requirement, 10% (based on cost) of the total materials should be harvested, extracted, or recovered within 500 miles (805 km) of the project site. An additional point is awarded for 20% regional materials. The majority of materials in pervious concrete and most other concrete are considered regional materials. Projects with large amounts of concrete can meet the required 10% or 20% regional materials to meet this credit (Fig. 12.3).

CHAPTER 13—REFERENCES

13.1—Referenced standards and reports

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designations. The users of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Association of State Highway & Transportation Officials (AASHTO)

M-157 Standard Specification for Ready-Mixed Concrete

T-180 Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54 kg (10-lb) Rammer and a 457-mm (18-in.) Drop

American Concrete Institute

301 Specifications for Structural Concrete

325.12R Guide for Design of Jointed Concrete Pavements for Streets and Local Roads

330R Guide for Design and Construction of Concrete Parking Lots

522.1 Specification for Pervious Concrete Pavement

ASTM International

C29/C29M Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate

C33/C33M Standard Specification for Concrete Aggregates

C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C42/C42M Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

C94/C94M Standard Specification for Ready-Mixed Concrete

C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

C138/C138M Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

C140 Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

C150/C150M Standard Specification for Portland Cement

C171 Standard Specification for Sheet Materials for Curing Concrete

C260 Standard Specification for Air-Entraining Admixtures for Concrete

C494/C494M Standard Specification for Chemical Admixtures for Concrete

C595/C595M Standard Specification for Blended Hydraulic Cements

C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

C666/C666M	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C989	Standard Specification for Slag Cement for Use in Concrete and Mortars
C1157/C1157M	Standard Performance Specification for Hydraulic Cement
C1240	Standard Specification for Silica Fume Used in Cementitious Mixtures
C1399	Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete
C1688/C1688M	Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete
D422	Standard Test Method for Particle-Size Analysis of Soils
D448	Standard Classification for Sizes of Aggregate for Road and Bridge Construction
D698	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))
D1557	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))
D1883	Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils
D2487	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
D3385	Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer
E1050	Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System

These publications may be obtained from the following organizations:

American Association of State Highway & Transportation Officials (AASHTO)
444 North Capitol Street N.W., Suite 249
Washington, DC 20001
www.aashto.org

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
www.concrete.org

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428
www.astm.org

13.2—Cited references

AASHTO, 1993, *Guide for Design of Pavement Structures*, Washington, DC, 640 pp.

Ahmad, S. H., and Shah, S. P., 1985, "Structural Properties of High Strength Concrete and its Implications for Precast Prestressed Concrete," *PCI Journal*, V. 30, No. 6, Nov./Dec., pp. 92-119.

Ashley, E., 2008, "Using Pervious Concrete to Achieve LEED™ Points," National Ready Mixed Concrete Association, Winter.

Atlanta Regional Commission, 2001, *Georgia Stormwater Management Manual*, pp. 3.3-33 and 3.3-40.

Baas, W. P., 2006, "Pervious Concrete Pavement Surface Durability in a Freeze-Thaw Environment where Rain, Snow and Ice Storms are Common Occurrences," Ohio Ready-Mixed Concrete Association, 4 pp.

Backstrom, M., 2000, "Ground Temperature in Porous Pavement During Freezing and Thawing." *Journal of Transportation Engineering*, V. 126, No. 5, Sept./Oct, pp. 375-381.

Bell, F. G., 1993, *Engineering Treatment of Soils*, Taylor and Francis, 302 pp.

Bhayani, B.; Holsen, T. M.; and Neithalath, N., 2007, "Investigations on the Efficiency of Enhanced Porosity Concretes in Containing Vehicular Oil Spills," *Proceedings in CD of the International Conference on Sustainability of Construction Materials and Structures*, Coventry, UK, 8 pp.

Brite/Euram Report, 1994, "Surface Properties of Concrete Roads in Accordance with Traffic Safety and Reduction of Noise," *Brite/Euram Project BE3415*, 138 pp.

Crouch, L. K.; Cates, M. A.; Dotson, V. J.; Honeycutt, K. R.; and Badoe, D. A., 2003, "Measuring the Effective Air Void Content of Portland Cement Pervious Pavements," *Cement, Concrete and Aggregates*, V. 25, No. 1, pp. 16-20.

Crouch, L. K.; Smith, N.; Walker, A. C.; Dunn, T. R.; and Sparkman, A., 2006, "Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter," *TRB 85th Annual Meeting Compendium of Papers*, 18 pp.

Das, B., 1993, *Principles of Geotechnical Engineering*, PWS Publishing Co., Boston, MA, p. 146.

Debo, T. N., and Reese, A. J., 2002, *Municipal Storm Water Management*, second edition, CRC Press, 976 pp.

Delatte, N.; Miller, D.; and Mrkajic, A., 2007, "Field Performance Investigation on Parking Lot and Roadway Pavements: Final Report," *RMC Research & Education Foundation*, 79 pp.

Deo, O.; Bhayani, B.; Holsen, T. M.; and Neithalath, N., 2008, "Modeling the Retention of Oil in Enhanced Porosity Concretes," *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Erickson, S., 2006, "Pervious Concrete Durability Testing," *Technical Report*, Viesko Quality Concrete, Salem, OR, 6 pp.

Florida Concrete and Products Association (FCPA), 1990, *Pervious Pavement Manual*, Orlando, FL, 57 pp.

Ferguson, B. K., 1994, *Stormwater Infiltration*, CRC Press, 288 pp.

Ferguson, B. K., 1998, *Introduction to Stormwater: Concept, Purpose, Design*, Wiley, 272 pp.

Ferguson, B. K., 2005, *Porous Pavements*, Taylor & Francis, New York, 600 pp.

Francis, A. M., 1965, "Early Concrete Buildings in Britain," *Concrete and Constructional Engineering*, London, V. 60, No. 2, Feb., pp. 73-75.

Ghafoori, N., 1995, "Development of No-Fines Concrete Pavement Applications," *Journal of Transportation Engineering*, V. 126, No. 3, May-June, pp. 283-288.

Haselbach, L. M., and Freeman, R. M., 2006," Vertical Porosity Distributions in Pervious Concrete Pavement," *ACI Materials Journal*, V. 103, No. 6, Nov.-Dec., pp. 452-458.

Haselbach, L. M.; Valavala, S.; and Montes, F., 2006, "Permeability Predictions for Sand Clogged Portland Cement Pervious Concrete Pavement Systems," *Journal of Environmental Management*, V. 81, No. 1, pp. 42-49.

Herod, S., 1981, "Porous Concrete Market Blooms in Greenhouse," *Modern Concrete*, Mar., pp. 40-44.

Houlsby, A. C., 1990, *Construction and Design of Cement Grouting*, John Wiley and Sons, 442 pp.

Jing, Y., and Guoliang, J., 2003, "Experimental Studies on Properties of Pervious Concrete Pavement Materials," *Cement and Concrete Research*, V. 33, No. 3, pp. 381-386.

Kevern, J. T., and Schaefer, V. R., 2008, "Temperature Response in a Pervious Concrete System Designed for Stormwater Treatment," *Proceedings of the American Society of Civil Engineers GeoCongress*, New Orleans, LA, pp. 1137-1144.

Korhonen, C. J., and Bayer, J. J., 1989, "Porous Portland Cement Concrete as an Airport Runway Overlay," *Special Report 89-12*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 20 pp.

Little, D. N.; Males, E. H.; Prusinski, J. R.; and Stewart, B., 2000, "Cementitious Stabilization, TRB Committee A2J01," 7 pp.

Low, K.; Harz, D.; and Neithalath, N., 2008, "Statistical Characterization of the Pore Structure of Enhanced Porosity Concretes," *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Mahboub, K.; Canler, J.; Rathbone, R.; Robl, T.; and Davis, B., 2008, "The Effects of Compaction and Aggregate Gradation on Pervious Concrete," *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Malhotra, V. M., 1969, "A Low-Cost Concrete Building," *Engineering News Record*, pp. 62-63.

Malhotra, V. M., 1976, "No-Fines Concrete—Its Properties and Applications," ACI JOURNAL, *Proceedings,* V. 73, No. 11, Nov., pp. 628-644.

Marolf, A.; Neithalath, N.; Sell, E.; Wegner, K.; Weiss, J.; and Olek, J., 2004, "Influence of Aggregate Gradation on the Acoustic Absorption of Enhanced Porosity Concrete," *ACI Materials Journal*, V. 101, No. 1, Jan.-Feb., pp. 82-91.

Mata, L., and Leming, M., 2008, "Sedimentation Effects on Pervious Concrete," *Proceedings of the 2008 National Ready Mixed Concrete Association Concrete Technology Forum*, Denver, CO.

Mathis, D. E., 1990, "Permeable Bases—An Update," *PCA*, No. 8, Nov., pp. 3-4.

Maynard, D. P., 1970, "A No-Fines Road," *Concrete Construction*, V. 15, No. 3, pp. 116-117.

Medico, J. J., Jr., 1975, "Porous Pavement," U.S. Patent No. 3870422.

Meininger, R. C., 1988, "No-Fines Pervious Concrete for Paving," *Concrete International*, V. 10, Aug., pp. 20-27.

Monahan, A., 1981, "Porous Portland Cement Concrete; the State of Art," U.S. Army Engineer Waterways Experiment Station, Structures Laboratory, Vicksburg, MS., Jan., 27 pp.

Montes, F. and Haselbach, L. M., 2006, "Measuring Hydraulic Conductivity in Pervious Concrete," *Environmental Engineering Science*, Nov., 2006.

Montes, F.; Valavala, S.; and Haselbach, L. M., 2005, "A New Test Method for Porosity Measurements of Portland Cement Pervious Concrete," *Journal of ASTM International*, Jan., V. 2, No. 1.

Mulligan, A., 2005, "Attainable Compressive Strength of Pervious Concrete Paving Systems," master's thesis, University of Central Florida, 132 pp.

National Ready Mixed Concrete Association (NRMCA), 2004, "Freeze-Thaw Resistance of Pervious Concrete," Silver Spring, MD, 17 pp.

National Ready Mixed Concrete Association (NRMCA), 2007, Text Reference for Pervious Concrete Contractor Certification, *Publication 2PPCRT*, NRMCA, Silver Spring, MD, Feb., 60 pp.

Neithalath, N., 2004, "Development and Characterization of Acoustically Efficient Cementitious Materials," PhD thesis, Purdue University, West Lafayette, IN, 269 pp.

Neithalath, N.; Weiss, W. J.; and Olek, J., 2003, "Development of Quiet and Durable Porous Portland Cement Concrete Paving Materials," *Final Report*, The Institute for Safe, Quiet, and Durable Highways, 179 pp.

Neithalath, N.; Weiss, W. J.; and Olek, J., 2005a, "Modifying the Surface Texture to Reduce Noise in Portland Cement Concrete Pavements," *Report* No. SN 2878, Portland Cement Association, Skokie, IL, 67 pp.

Neithalath, N.; Weiss, J.; and Olek, J., 2005b, "Modeling the Effects of Pore Structure on the Acoustic Absorption of Enhanced Porosity Concrete," *Journal of Advanced Concrete Technology*, Japan Concrete Institute, V. 3, No. 1, Feb., pp. 29-40.

Neithalath, N.; Weiss, J.; and Olek, J., 2006, "Characterizing Enhanced Porosity Concrete Using Electrical Impedance to Predict its Acoustic and Hydraulic Performance," *Cement and Concrete Research*, V. 36, No. 11, pp. 2074-2085.

Nelson, P. M., and Phillips, S., 1994, "Designing Porous Road Surfaces to Reduce Traffic Noise," *Transportation Research Laboratory Annual Review*, TRL, Crow Thorne, England, 58 pp.

Nissoux, J. L.; Gnagne, C.; Marzin, J.; Lefebvre, J.-P.; and Pipien, G., 1993, "A Pervious Cement Concrete Wearing Course Below 73 dB(A)," *Proceedings of the Fifth International Conference on Concrete Pavement and Rehabilitation*, Purdue University, IN, V. 2, pp. 269-284.

Offenberg, M. 2005a, "Producing Pervious Pavements," *Concrete International*, V. 27, No. 3, Mar., pp. 50-54.

Offenberg, M., 2005b, "Pervious Concrete Pavement Permitting," *Land Development Today*, V. 1, No. 8, Aug., pp. 6-10.

Offenberg, M., and Davy, M., 2008, "Development of a Test Method for Assessing the Surface Durability of Pervious Concrete," *Proceedings of the National Ready-Mixed Concrete Association Concrete Technology Forum*, Denver, CO, 30 pp.

Onstenk, E.; Aguado, A.; Eickschen, E.; and Josa, A., 1993, "Laboratory Study of Porous Concrete for Its Use as Top Layer of Concrete Pavements," *Proceedings of the Fifth International Conference on Concrete Pavement and Rehabilitation*, Purdue University, IN, V. 2, pp. 125-139.

Paine, J. E., 1990, "Stormwater Design Guide, Portland Cement Pervious Pavement," Florida Concrete and Products Association, Orlando, FL, 13 pp.

Pindado, M. A.; Aguado, A.; and Josa, A., 1999, "Fatigue Behavior of Polymer-Modified Porous Concretes," *Cement and Concrete Research*, V. 29, No. 7, pp. 1077-1083.

Pratt, C.; Wilson, S.; and Cooper, P., 2002, "Source Control Using Constructed Pervious Surfaces. Hydraulic, Structural and Water Quality Performance Issues," CIRIA, 152 pp.

RMC Research Foundation, 2006, *Ready-Mixed Concrete Industry LEED™ Reference Guide*, Silver Spring, MD.

Rushton, B., 2000, "Low Impact Parking Lot Design Reduces Runoff and Pollutant Loads," Southwest Florida Water Management District, Brooksville, FL, 225 pp.

Schaefer, V. R.; Wang, K.; Suleiman, M. T.; and Kevern, J. T., 2006, "Mix Design Development for Pervious Concrete in Cold Weather Climates," National Concrete Pavement Technology Center, 85 pp.

SI Concrete Systems, 2002, "Fiber-Reinforced Pervious Concrete," *Project* 2120-36, Chattanooga, TN, Oct. 25.

Soil Conservation Service, 1986, "Urban Hydrology for Small Watersheds," *Technical Release* No. 55, Soil Conservation Service, U.S. Department of Agriculture, Washington, DC, 160 pp.

St. John's River Water Management District (SJRWMD), 1999, *Applicant's Handbooks: Regulation of Stormwater Management Systems*, Palatka, FL, 285 pp.

Suleiman, M.; Kevern, J.; Schaefer, V. R.; and Wang, K., 2006, "Effect of Compaction Energy on Pervious Concrete Properties," *Proceedings of the NRMCA Concrete Technology Forum: Focus on Pervious Concrete*, Nashville, TN, 8 pp.

Tamai, M.; Mitzuguchi, H.; Hatanaka, S.; Katahira, H.; Makazawa, T.; Yanagibashi, K.; and Kunieda, M., 2004, "Design, Construction, and Recent Applications of Porous Concrete in Japan," *Proceedings of the JCI Symposium on Design, Construction, and Recent Applications of Porous Concrete*, Japan Concrete Institute, Tokyo, 15 pp.

U.S. Bureau of Reclamation, 1947, "The Durability of Porous Concrete," Materials Laboratories Report No. 3-369, U.S. Department of the Interior, Washington, DC.

Valavala, S.; Montes, F.; and Haselbach, L. M., 2006, "Area Rated Rational Coefficient Values for Portland Cement Pervious Concrete Pavement," *Journal of Hydrologic Engineering*, ASCE, V. 11, No. 3, pp. 257-260.

Wang, K.; Schaefer, V. R.; Kevern, J. T.; and Suleiman, M. T., 2006, "Development of Mix Proportion for Functional and Durable Pervious Concrete," *Proceedings of the NRMCA Concrete Technology Forum: Focus on Pervious Concrete*, Nashville, TN, 12 pp.

Wang, K.; Kevern J.; and Schaefer, V., 2008, "Self Consolidating Pervious Concrete for Overlay Applications," *Proceedings of the National Ready-Mixed Concrete Association Concrete Technology Forum*, Denver, CO.

Wanielista, M.; Chopra, M.; Offenberg, M.; Spence, J.; and Ballock, C., 2005, "Performance of Pervious Concrete Pavements," Presentation: Stormwater Management for Highways, Transportation Research Board TRB AFB60, Washington, DC.

Wanielista, M.; Chopra, M.; Spence, J.; and Ballock, C., 2007, "Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit," Stormwater Management Academy, University of Central Florida, 81 pp.

Weaver, K., 1991, *Dam Foundation Grouting*, ASCE Press, pp. 29-30.

Wimberley, J. D.; Leming, M. L.; and Nunez, R. A., 2001, *Evaluation of Mechanical and Hydrological Properties of High-Voids Pervious Concrete*, North Carolina State University, Raleigh, NC, 39 pp.

Winer, R. R., 2000, *National Pollutant Removal Database for Stormwater Treatment Practices*, second edition, Center for Watershed Protection, Ellicott City, MD, 29 pp.

Wingerter, R., and Paine, J. E., 1989, *Field Performance Investigation*, Portland Cement Pervious Pavement, Concrete and Products Association, Orlando, FL, 16 pp.

Yang, J., and Jiang, G., 2003, "Experimental Study on Properties of Pervious Concrete Pavement Materials," *Cement and Concrete Research*, V. 33, pp. 381-386.

Yang, Z.; Brown, H.; and Cheney, A., 2006, "Influence of Moisture Conditions of Freeze and Thaw Durability of Portland Cement Pervious Concrete," *Proceedings of the NRMCA Concrete Technology Forum: Focus on Pervious Concrete*, 15 pp.

Yen, P. T.; Sundaram, P. N.; and Godwin, W. A., 2002, "Pumped-in-Place Permeable Grout Systems, Permeation Grouting," Bechtel Corporation Technical Grant, pp. 1-44.

Zouaghi, A.; Kumagai, M.; and Nakazawa, T., 2000, "Fundamental Study on Some Properties of Pervious Concrete and Its Applicability to Control Stormwater Run-off," *Transactions of the Japan Concrete Institute*, V. 22.

American Concrete Institute®
Advancing concrete knowledge

As ACI begins its second century of advancing concrete knowledge, its original chartered purpose remains "to provide a comradeship in finding the best ways to do concrete work of all kinds and in spreading knowledge." In keeping with this purpose, ACI supports the following activities:

- Technical committees that produce consensus reports, guides, specifications, and codes.
- Spring and fall conventions to facilitate the work of its committees.
- Educational seminars that disseminate reliable information on concrete.
- Certification programs for personnel employed within the concrete industry.
- Student programs such as scholarships, internships, and competitions.
- Sponsoring and co-sponsoring international conferences and symposia.
- Formal coordination with several international concrete related societies.
- Periodicals: the *ACI Structural Journal* and the *ACI Materials Journal*, and *Concrete International*.

Benefits of membership include a subscription to *Concrete International* and to an ACI Journal. ACI members receive discounts of up to 40% on all ACI products and services, including documents, seminars and convention registration fees.

As a member of ACI, you join thousands of practitioners and professionals worldwide who share a commitment to maintain the highest industry standards for concrete technology, construction, and practices. In addition, ACI chapters provide opportunities for interaction of professionals and practitioners at a local level.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

Report on Pervious Concrete