

Report on Pervious Concrete

Reported by ACI Committee 522



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First Printing: March 2010
Errata as of 8/8/2017

Report on Pervious Concrete

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ISBN 978-0-87031-364-6

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Report on Pervious Concrete

Reported by ACI Committee 522

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

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

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

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CONTENTS

Chapter 1—Introduction and scope, p. 2

- 1.1—Introduction
- 1.2—Scope

Chapter 2—Notation and definitions, p. 3

- 2.1—Notation
- 2.2—Definitions

Chapter 3—Applications, p. 3

- 3.1—General
- 3.2—Building applications: history
- 3.3—Pavement applications
- 3.4—Other applications

Chapter 4—Materials, p. 6

- 4.1—General
- 4.2—Aggregates
- 4.3—Cementitious materials
- 4.4—Water
- 4.5—Admixtures

Chapter 5—Properties, p. 7

- 5.1—General
- 5.2—Compressive strength

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

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- 5.3—Flexural strength
- 5.4—Void content/density
- 5.5—Pore sizes
- 5.6—Percolation rate
- 5.7—Durability
- 5.8—Toughness
- 5.9—Acoustic absorption

Chapter 6—Pervious concrete mixture proportioning, p. 12

- 6.1—General
- 6.2—Materials
- 6.3—Water-cementitious material ratio
- 6.4—Void content
- 6.5—Amount of coarse aggregate
- 6.6—Paste volume, cement, and water contents
- 6.7—Proportioning procedure
- 6.8—Typical ranges of materials

Chapter 7—Pervious pavement design, p. 15

- 7.1—Introduction
- 7.2—Structural design
- 7.3—Stormwater management design
- 7.4—Other considerations

Chapter 8—Pervious pavement construction, p. 20

- 8.1—General construction principles
- 8.2—Subgrade/subbase preparation
- 8.3—Placing
- 8.4—Consolidation
- 8.5—Jointing
- 8.6—Curing and protection
- 8.7—Cold weather protection
- 8.8—Hot weather protection
- 8.9—Repairing pervious concrete pavements
- 8.10—Maintenance

Chapter 9—Quality control inspection and testing, p. 26

- 9.1—General
- 9.2—Preconstruction inspection and testing
- 9.3—Inspection and testing during construction
- 9.4—Post-construction inspection and testing

Chapter 10—Performance, p. 27

- 10.1—General
- 10.2—Changes in infiltration rates
- 10.3—Structural distress
- 10.4—Surface distress
- 10.5—Resistance to freezing and thawing

Chapter 11—Limitations, potential applications, and research needs, p. 29

- 11.1—Pervious concrete in cold climates
- 11.2—Strength determinations and limitations
- 11.3—Characterization of the material structure
- 11.4—Freezing-and-thawing and cold climate applications
- 11.5—Porous grout
- 11.6—Stormwater management

- 11.7—Environmental filtering/remediation potential
- 11.8—Surface deterioration and repair
- 11.9—Development and standardization of broader testing methods
- 11.10—Non-destructive determination of performance and properties
- 11.11—Urban heat island effect, carbonation, and other thermal properties
- 11.12—Other novel applications and uses

Chapter 12—The environment and pervious concrete, p. 33

- 12.1—Pervious concrete and the LEED™ green building rating system

Chapter 13—References, p. 36

- 13.1—Referenced standards and reports
- 13.2—Cited references

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/ft² (81 to 730 L/min/m²) 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

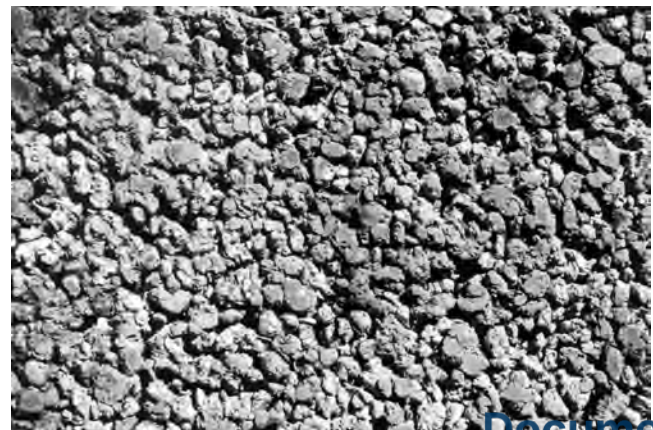


Fig. 1.1—Pervious concrete pavement texture on parking lot.

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_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 base course type 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.

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.

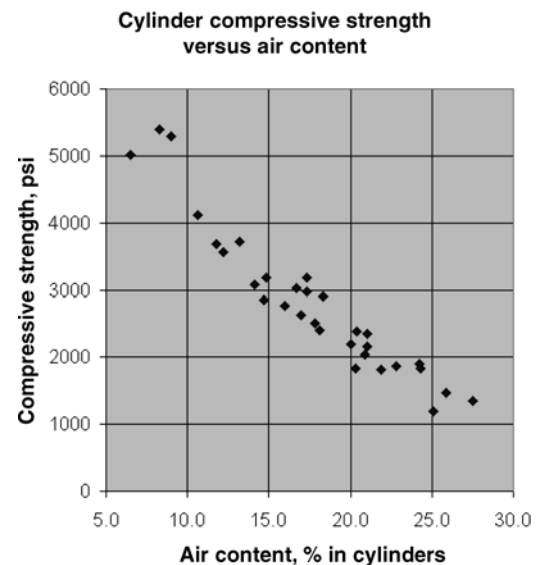


Fig. 5.1—Relationship between air content and compressive strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

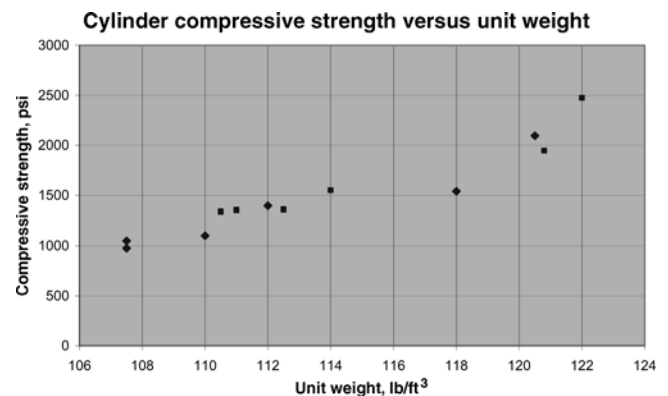


Fig. 5.2—Relationship between unit weight and compressive strength for pervious concrete (Mulligan 2005) (1 psi = 0.006895 MPa; 1 lb/ft³ = 16.02 kg/m³).

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 a 1% increase in compressive strength was observed when the vibration

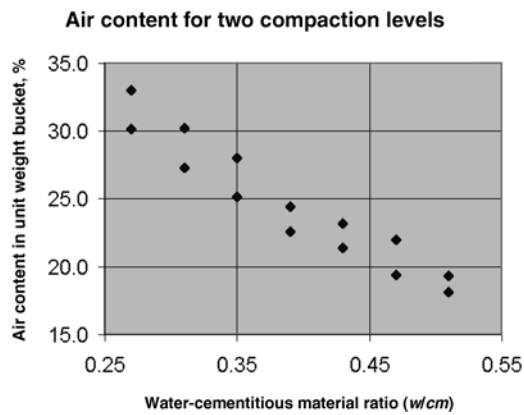


Fig. 5.3—Relationship between air content and compaction energy for pervious concrete (Meininger 1988).

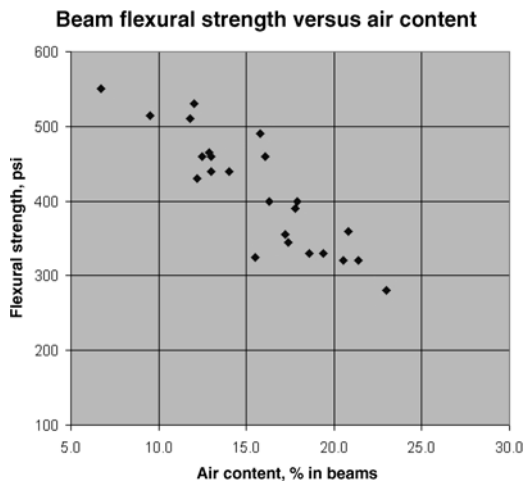


Fig. 5.4—Relationship between air content and flexural strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

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

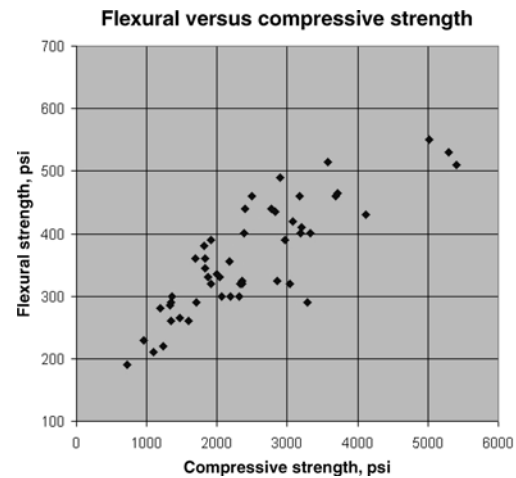


Fig. 5.5—Relationship between flexural strength and compressive strength for pervious concrete (Meininger 1988) (1 psi = 0.006895 MPa).

(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).

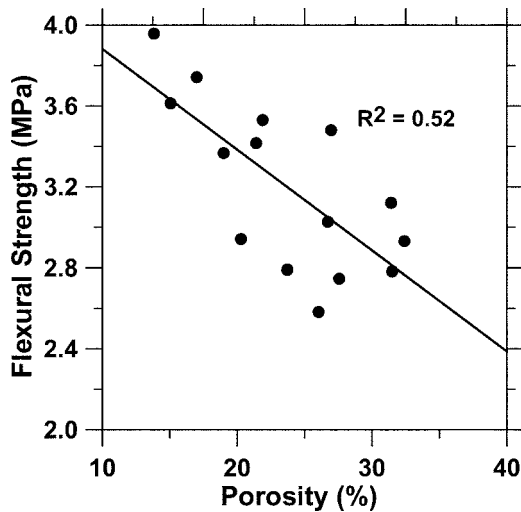


Fig. 5.6—Relationship between flexural strength and porosity for pervious concrete (1 psi = 0.006895 MPa).

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.

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

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

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.

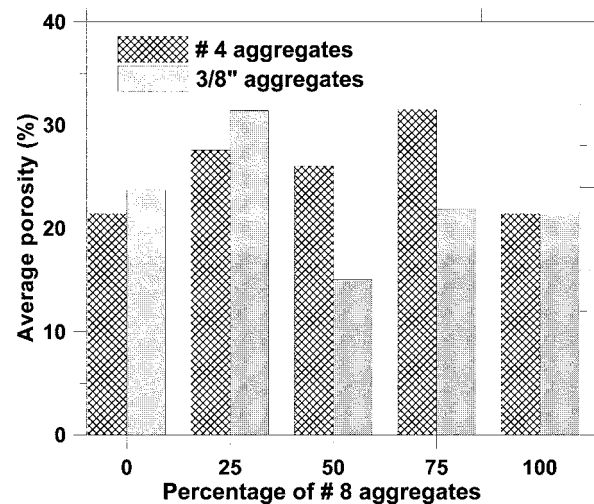


Fig. 5.7—Influence of aggregate size and gradation on the porosity of pervious concretes.

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/ft³ (1680 to 1920 kg/m³). 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

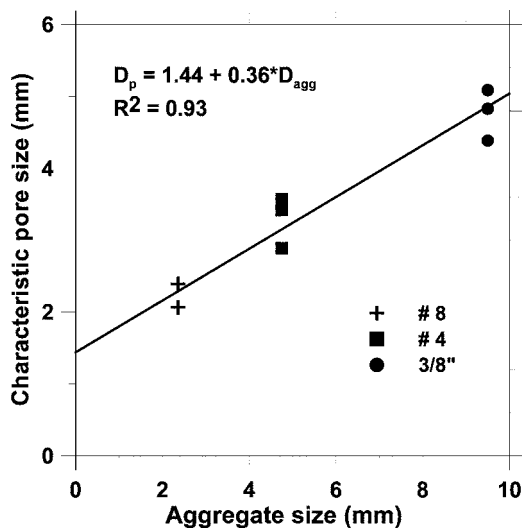


Fig. 5.8—Influence of aggregate size on the pore size of single-sized aggregate pervious concrete mixtures.

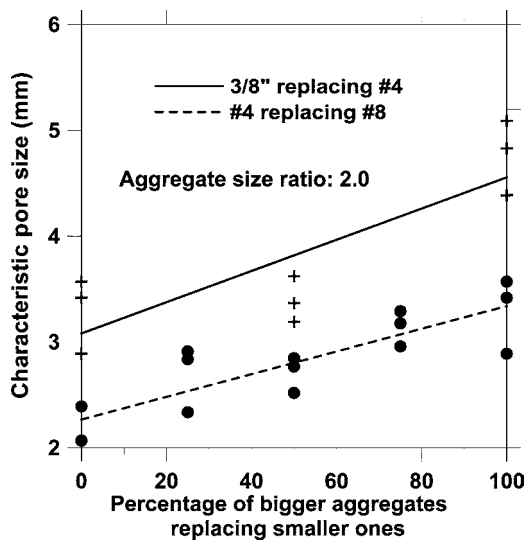


Fig. 5.9—Influence of aggregate blending on the pore size of pervious concrete.

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.

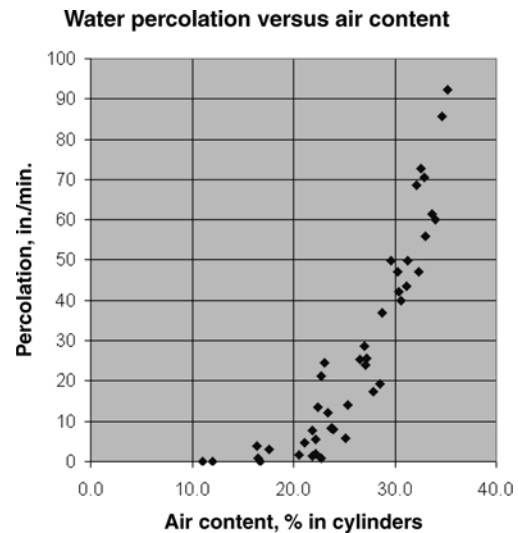


Fig. 5.10—Relationship between air content and percolation rate for pervious concrete (Meininger 1988) (1 psi = 0.06895 MPa).

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 to be approximately 0.01 m/s (Brite/Euram Report 1994). Another study (Nissoux et al. 1993) reports a permeability of 0.88 gal./ft²/s (36 L/m²/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

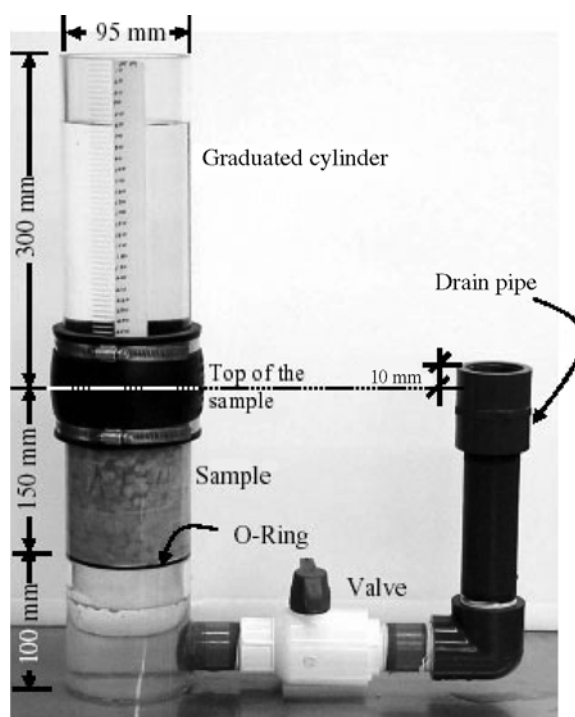


Fig. 5.11—Apparatus for measuring permeability of pervious concrete by a simple falling-head permeameter (Neithalath et al. 2003) (1 in. = 25.4 mm).

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.

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 C666M requires a standard 300 cycles for the test). The relative

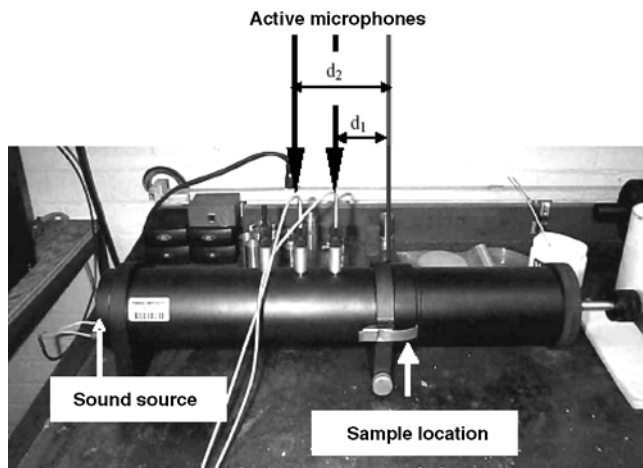


Fig. 5.12—Impedance tube for measuring the sound absorption characteristics of pervious concrete (Neithalath 2004; Marolf et al. 2004).

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 snugly. The sample assembly is placed against a rigid backing at one end of the impedance tube, which is equipped with a sound source. A plane acoustic wave is generated by the sound source and propagates along the tube axis. Microphones placed along the tube's length are used to detect the sound wave pressure transmitted to the sample and portion of the wave that is reflected (ASTM E1050). The pressure reflection coefficient R is the ratio of the pressure of reflected wave to that of incoming wave, at a particular frequency.

The absorption coefficient 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