Mix Design Development for Pervious Concrete in Cold Weather Climates

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16. Abstract

Portland cement pervious concrete (PCPC) is being used more frequently due to its benefits in reducing the quantity of runoff water, improving water quality, enhancing pavement skid resistance during storm events by rapid drainage of water, and reducing pavement noise. In the United States, PCPC typically has high porosity and low strength, which has resulted in the limited use of pervious concrete, especially in hard wet freeze environments (e.g., the Midwestern and Northeastern United States and other parts of the world). Improving the strength and freeze-thaw durability of pervious concrete will allow an increase in its use in these regions. The objective of this research is to develop a PCPC mix that not only has sufficient porosity for stormwater infiltration, but also desirable strength and freeze-thaw durability. In this research, concrete mixes were designed with various sizes and types of aggregates, binder contents, and admixture amounts. The engineering properties of the aggregates were evaluated. Additionally, the porosity, permeability, strength, and freeze-thaw durability of each of these mixes was measured. Results indicate that PCPC made with single-sized aggregate has high permeability but not adequate strength. Adding a small percent of sand to the mix improves its strength and freeze-thaw resistance, but lowers its permeability. Although adding sand and latex improved the strength of the mix when compared with single-sized mixes, the strength of mixes where only sand was added were higher. The freeze-thaw resistance of PCPC mixes with a small percentage of sand also showed 2% mass loss after 300 cycles of freeze-thaw. The preliminary results of the effects of compaction energy on PCPC properties show that compaction energy significantly affects the freeze-thaw durability of PCPC and, to a lesser extent, reduces compressive strength and split strength and increases permeability.

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EXECUTIVE SUMMARY

Pervious pavements allow stormwater to percolate through the voids in the pavement, which reduces the amount of runoff water. In the United States, pervious pavements are mainly used in sidewalks, parking lots, and low traffic density areas. Unlike other pavement systems, the pervious layer not only needs to posses the required strength and freeze-thaw durability to support the applied loads and resist environmental conditions, but must also have adequate permeability for the design storm of a specific region. Pervious concretes in the United States have been reported to have adequate void ratios but strengths lower than those required for structural concrete used in parking lots and pavement applications. Furthermore, freeze-thaw test results and pervious concrete pavement installations in hard wet freezing regions of the United States (e.g., Midwest and Northeast) have been limited. Low strength values and lack of freeze-thaw durability test results have limited the use of pervious concrete in hard wet freezing regions.

This report summarizes the results of research performed at the Portland Cement Concrete Pavement Materials and Research Laboratory at Iowa State University to develop a pervious concrete with freeze-thaw resistance that possesses the required compressive strength and adequate permeability.

Relevant Literature

The increasing interest in pervious concrete in the United States is due to the recent Clean Water Act and other Environmental Protection Agency regulations, which require decreasing the amount of water runoff and initially treating the runoff. The advantages of using pervious concrete also include improving skid resistance by removing water during rainy days, reducing noise, minimizing the heat island effect in large cities, preserving native ecosystems, and minimizing costs in some cases. However, the engineering properties reported in the literature from the United States indicate a high void ratio, low strength, and limited freeze-thaw test results.

A typical cross-section of the pervious pavement used in parking lots consists of a pervious concrete layer with a thickness of 4 to 6 inches, a permeable base with a thickness up to 18 inches, and a permeable subgrade. If the subgrade permeability is low, drainage pipes can be used to drain water, but drainage pipes increase the cost of the system.

Typical pervious concrete mix designs used in the United States consist of cement, single-sized coarse aggregate (generally a size between one inch and the No. 4 sieve), and a water to cement ratio ranging from 0.27 to 0.43. Reported properties of pervious concrete in the United States indicate that the 28-day compressive strength of pervious concrete ranges from 800 psi to 3,000 psi, with void ratios ranging from 14% to 31%, and permeability ranging from 36 to 864 inches/hour.

Mixing Proportion and Mixing Procedures

Two types of single-sized coarse aggregate, crushed limestone and river gravel, were used in this study. Three sizes of single-sized river gravel were used: (1) 1/2-inch size, with 100% passing the 5/8-inch and 100% retained on the 1/2-inch sieve, (2) 3/8-inch size, with 100% passing the 1/2-inch and 100% retained on the 3/8-inch sieve, and (3) No. 4 size, with 100% passing the 3/8-inch and 100% retained on the No. 4 sieve. Additionally, single-sized 3/8-inch crushed limestone and two gradations of commercially available river gravel, known as pea gravel, were used. Furthermore, the effects of using a small percentage of sand, and the effects of using latex and silica fume on pervious concrete engineering properties were investigated.

The dry rodded unit weight, void ratio, specific gravity, and abrasion resistance of these aggregates were measured. The results indicate that river gravel has a higher unit weight and abrasion resistance than crushed limestone.

Two mixing procedures were used to prepare the samples. Initial specimens were prepared with 3/8-inch river gravel using a traditional concrete mixing procedure in which aggregate, water, and admixtures were combined before the addition of the cement. Using this mixing procedure, it was observed that the sample failed at the interface between the cement paste and the aggregate. A second mixing procedure was used to improve the bond between the cement paste and the aggregate by dry mixing a small amount of cement (<5% by mass) with the aggregate until completely coated (about one minute). Next, the remaining cement and water (with or without high-range water reducer) was added. Finally, the concrete was mixed for three minutes, allowed to rest for three minutes, and then mixed for an additional two minutes before casting. Samples prepared using this modified mixing procedure failed through the aggregate, which increased the seven-day compressive strength of the mix. However, mixes made with crushed limestone did not show a significant increase in strength due to the textured nature of this aggregate.

The cement content used in the prepared mixes was varied to reduce excess paste content. A binder to aggregate ratio of 0.21 and a water to cement ratio of 0.27 was found to be optimum, considering strength, permeability, and void ratio. Mixes were prepared using percentages of latex ranging from 0% to 15% by weight of solids to cementitious materials. When comparing the seven-day strengths, the optimum latex content was found to be 10%.

All specimens were prepared by rodding 25 times in three layers, while applying a vibration for five seconds after rodding each layer. To evaluate the effect of compaction on pervious concrete properties, two vibrating amplitudes of 0.005 and 0.0034 inches, which were identified as regular and low compaction energies, respectively, were used.

Findings and Recommendations

- Sand and/or latex increase strength and reduce permeability for both river gravel and limestone aggregate types. Mixes containing only sand had a greater increase in strength than the mixes containing sand and latex. Mixes containing silica fume had higher voids ratios and lower strengths than mixes without.
- Pervious concrete engineering properties vary as a function of void ratio. It was found

that compressive strength decreases linearly as the void ratio increases, unit weight decreases linearly as the void ratio increases, and permeability increases exponentially as the void ratio increases, with rapid increase in permeability for void ratios greater than 25%.

- The overall results at regular compaction energy indicate that mixes with void ratios ranging from 15% to 19% produced seven-day compressive strengths ranging from 3,300 psi and 2,900 psi and a permeability ranging from 135 inches/hour to 240 inches/hour. These mixes had unit weights between of 127 and 132 pcf.
- Freeze-thaw test results indicate that a mass loss of 15% represents the terminal serviceability acceptable level for pavement surfaces. Mixes that contained sand, latex, or a mix of latex and sand showed better freeze-thaw resistance than baseline mixes with no sand, no latex, or neither. Baseline river gravel mix with sand showed the best freeze-thaw resistance.
- Well-designed pervious concrete mixes can meet strength, permeability, and freeze-thaw resistance requirements for cold weather climates. Mix No. 4-RG-S7 with air entrainment showed the best freeze-thaw durability, with 2% mass loss after 300 freeze-thaw cycles.
- A limited number of aggregate sizes and types were evaluated in this study. Although limited types of aggregate were used, results showed that aggregate properties significantly affect portland cement pervious concrete (PCPC) properties. Creating freeze-thaw durable PCPC mixes that will function throughout the United States requires the evaluation of a larger variety of aggregates that represent typical varieties found across the United States. Evaluating more aggregate types will allow for the development of a minimum aggregate properties specification that produces durable PCPC.
- Throughout this study, results have indicated that compaction is an important factor that affects the properties of PCPC. More research is required to determine the relationship between compaction energy and PCPC properties including strength, void ratio, permeability, and freeze-thaw durability. By determining this relationship, placing methods can be modified to produce high-quality PCPC, and performance can be predicted through calibration with lab-scale methods.
- This study evaluated silica fume, latex, and sand as methods of strength improvement. Other materials exist that may improve PCPC strength and durability. For instance, polypropylene fibers add split strength and durability to standard concrete and need to be evaluated in pervious concrete. Preliminary results show that fibers increase both compressive and split strength without affecting void ratio or permeability.

Future Research

Although a limited number of aggregate sizes and types were evaluated in this study, we conclude that aggregate engineering properties (e.g., abrasion resistance, which indicates strength) must be evaluated to design high-quality PCPC. Creating freeze-thaw durable PCPC mixes that will function throughout the United States will require the evaluation of a larger variety of aggregates that represent typical varieties found across the United States. Evaluating more aggregate types will allow the development of a specification for the minimum aggregate quality required to produce durable PCPC.

More research is also required to determine the relationship between compaction energy and PCPC properties including strength, void ratio, permeability, and freeze-thaw durability. By determining this relationship, standardized methods for PCPC placement can be developed and modified to produce high-quality PCPC, and performance can be predicted through calibration with lab-scale methods.

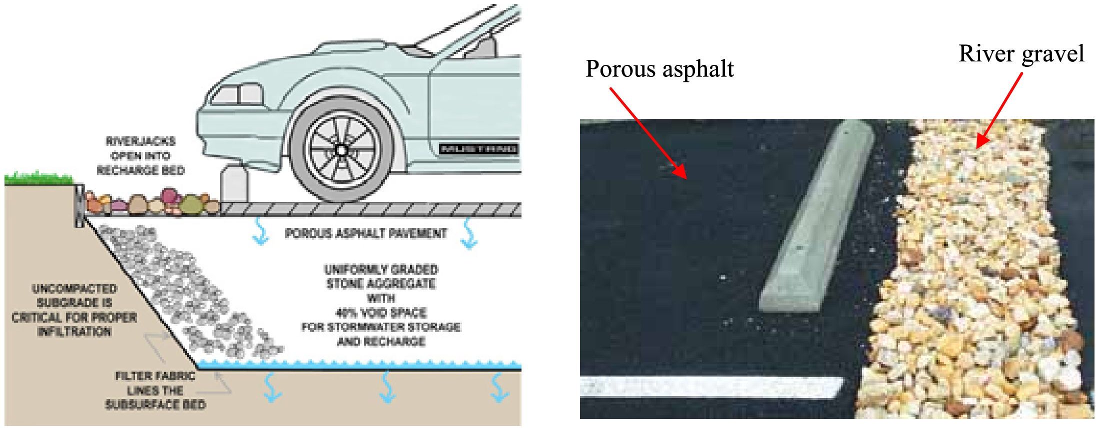
This study evaluated the effects of using silica fume, latex, and sand to improve PCPC properties. However, other materials exist that may increase PCPC strength and durability. For instance, polypropylene fibers add split strength and durability to standard concrete and should be evaluated in pervious concrete. Preliminary results show that fibers increase both compressive and split strength without affecting void ratio or permeability.

INTRODUCTION

Background

To meet the requirements of the Federal Water Pollution Control and Flood Disaster Protection Acts of the United States, the Franklin Institute Research Laboratories developed pervious asphalt pavement systems in the early 1970s (Diniz 1980). A small amount of fines was removed from a standard asphalt mix to produce a mix with high porosity that allowed stormwater infiltration. However, relatively low porosity is required to maintain the required strength and long-term durability. To infiltrate the desired amount of water, additional infiltration strips must be constructed around the site (see Figure 1). Construction costs for porous asphalt are greater than standard asphalt pavement due to the construction of the underlying infiltration cell (Adams 2003). An Environmental Protection Agency (EPA) factsheet (1999) lists clogging of porous asphalt as the primary method of failure.

More recently, amendments to the Clean Water Act (1999), which require reducing the quantity of stormwater runoff and providing initial water quality treatment, increased interest in developing new porous pavement materials and enhancing the properties of currently used materials. Portland cement pervious concrete (PCPC) is one solution used to reduce the volume of direct water runoff from pavements and to enhance the quality of stormwater (Water Environment Research Foundation 2005). Other reported advantages of pervious concrete include reducing noise, improving skid resistance, reducing owner cost, preserving native ecosystems and minimizing the heat island effect in large cities (Ferguson 2005; Tennis et al. 2004). The disadvantages of pervious concrete include yearly or bi-yearly maintenance to unclog voids and restore permeability and the possibility of contaminating the groundwater, depending on the soil conditions (EPA 2004). Furthermore, the low strength and durability of pervious concrete has resulted in failures at an early stage of pavement life.



(a) Porous pavement cross-section (Cahill 2005) (b) Recharge bed near porous asphalt pavement (Adams 2003)

Figure 1. Porous asphalt pavement design

However, the durability of pervious concrete in freeze-thaw environments has not been well documented, which has hindered the use of PCPC in the Northern and Midwestern United States.

Research Objective

The primary objective of this study is to develop a PCPC mix that is freeze-thaw resistant and that has the required compressive strength and adequate permeability for pavement applications.

Approach

Generally, concrete strength and durability decrease as the void ratio increases. The challenge of the current study is to increase the void ratio of the concrete without significantly reducing strength and freeze-thaw durability. Although PCPC improves the quality and reduces the quantity of stormwater runoff, PCPC is not widely used in wet-freeze environments due to its reported low strength and low freeze-thaw durability. The ultimate goal of this study is to produce a freeze-thaw durable pervious concrete that can be used reliably in a paving system. The following approaches were adopted to accomplish this goal:

1. Determine the effect of aggregate type and size on the void ratio and strength of PCPC, which will increase the strength while providing sufficient porosity for stormwater infiltration.
2. Determine the effect of various admixtures, such as silica fume, latex, and sand, on PCPC properties.
3. Determine the relationships between void ratio, permeability, and strength in PCPC to better identify potential durable mixes.
4. Determine the freeze-thaw durability of PCPC mixes.

Research Scope

Pervious concrete mixes were prepared using two types of single-sized coarse aggregate: crushed limestone and river gravel. These mixes included single-sized aggregates (1/2-inch, 3/8-inch, and No. 4 sieve sizes), single-sized aggregate with a small amount of sand, and commercially available pea gravel. Furthermore, the effects of latex and silica fume on pervious concrete engineering properties were investigated.

Initially, small-scale mixes were prepared (Phase I) to evaluate the properties of pervious concrete at seven days. Selected mixes were then prepared using large-scale mixes (Phase II) to evaluate the time development of strength, permeability, split strength, and freeze-thaw durability. The effects of compaction on pervious concrete engineering properties were also evaluated.

LITERATURE SURVEY

General Review of the Literature

To meet the requirements of the Federal Water Pollution Control and Flood Disaster Protection Acts of the United States, the Franklin Institute Research Laboratories developed pervious asphalt pavement systems in the early 1970s (Diniz 1980). More recently, amendments to the Clean Water Act (1999), which require reducing the quantity of stormwater runoff and providing initial water quality treatment, increased the interest in developing new porous pavement materials and enhancing the properties of currently used materials. PCPC is one of the methods used to reduce the volume of direct water runoff from pavements and to enhance the quality of stormwater (Water Environment Research Foundation 2005).

Pervious concrete pavement has been used for over 30 years in England and the United States (Youngs 2005; Maynard 1970). PCPC is also widely used in Europe and Japan for roadway applications as a surface course to improve skid resistance and reduce traffic noise (Beeldens 2001; Kajio et al. 1998).

Currently, full-depth PCPC is used in the United States for parking lots, pathways, and, in some cases, low-volume roads for stormwater applications (Tennis et al. 2004). PCPC is used to allow stormwater to infiltrate through the pavement and reduce or eliminate the need for additional control structures, such as retention ponds. The large surface area of PCPC also helps clean a majority of the pollutants in the stormwater and allows the natural attenuation of microbes to reduce their concentration. Instead of accumulating in nearby surface waters, the pollutants are trapped in the pavement system, thereby increasing overall water quality.

As stormwater legislation becomes more stringent, methods have been developed to deal with the new regulations. To alleviate flooding in densely populated areas and to improve surface water quality, the National Pollutant Discharge Elimination System (NPDES) was created to issue permits. Private owners and public agencies are required to reduce the amount of stormwater runoff and reduce the contaminants in the runoff water to near pre-development levels (Federal Register 2004). These reductions can be achieved by detention ponds and vegetative buffers (WERF 2005). However, pervious concrete is an effective tool for achieving these reductions in stormwater runoff and initially treating stormwater.

The open structure of PCPC also has other benefits, including the following: (1) improved skid resistance, (2) reduced noise levels, (3) fast melting of snow, and (4) prevention of faulting on sidewalks and recreational trails by allowing trees to grow with no root heave (Kajio et al. 1998; Tennis et al. 2004; Ferguson 2005).

The literature review of this report includes three main areas:

1. Typical construction materials used in PCPC mixes and PCPC material properties
2. Design and construction considerations and methods, including maintenance practices
3. Environmental benefits of PCPC pavement

Construction Materials

The porosity in PCPC is created by the reduction or elimination of fine aggregate from the normal concrete mix. Standard pervious concrete used in the United States is a mixture of a single-sized coarse aggregate and cement combined at low water to cement ratios (Florida Concrete and Products Association Inc. 2000; Tennis et al. 2004). Table 1 shows typical PCPC mix proportions used in the United States, as reported by the National Ready Mix Concrete Association (NRMCA).

Table 1. Typical mix design for existing PCPC in the United States (NRMCA 2004)

Property	Specification
Cement content	300 to 600 lbs/yd^3
Coarse aggregate content	2,400 to 2,700 lbs/yd^3
Fine aggregate content	0 lbs/yd^3
Water-cement ratio	0.27 to 0.43

The coarse aggregate used in pervious concrete is typically either rounded river gravel or a crushed stone. The size of single-sized aggregate commonly used in PCPC ranges from aggregate retained on the No. 4 sieve to 3/4-inch aggregate, with 1-inch aggregate used in some instances (Tennis et al. 2004). The water to cement ratio ranges from 0.25 to 0.35, with water reducers causing typical PCPC mixes to have a slump less than 1 inch, as measured by ASTM C143 (Tennis et al. 2004). The open structure of PCPC increases the exposed surface area; therefore, hydration retarders are often used to extend mix life and facilitate proper placement (Pacific Southwest Concrete Alliance 2004). If the mix is to be used in a cold weather area, air-entrainment has been shown to improve freeze-thaw protection (Neithalath 2003; Tamai and Yoshida 2003). The NRMCA suggests using 4% to 8% air entrainment with a spacing factor of 0.01 inches to provide satisfactory freeze-thaw resistance (NRMCA 2004).

PCPC mixes used in Europe and Japan, which are made with small-sized aggregate and sometimes the addition of a small amount of fine aggregate (e.g., sand), provide a strong surface coarse for roadway application. In both Europe and Japan, No. 8 size crushed gravel has been used with sand to improve the strength and durability of pervious concrete (Kajio et al. 1998; Beeldens et al. 2003). Experiments have incorporated up to 15% fine sand, as a mass ratio of fine aggregate to coarse aggregate, while 5% to 10% was found to be an optimal amount to improve strength (Beeldens 2001; Olek et al. 2003). Furthermore, latex emulsion has also been used to improve PCPC strength. A ratio of 10% latex solids to cementitious materials was found to provide the best combination of improved tensile strength and water reduction (Beeldens 2001). This is similar to the percent of latex used in normal latex-modified concrete (Wang et al. 2005).

PCPC Material Properties

Table 2 summarizes the PCPC material properties found in the U.S. and international literature. This table shows that the void ratio of PCPC ranges from 11% to 35%, with a 28-day compressive strength between 800 psi and 4650 psi, permeability between 36 inches/hour and 756 inches/hour, flexural strength between 150 psi and 1085 psi, and unit weight between 100 pcf and 130 pcf. However, the permeability of the mix with the highest strength was not reported, and the mix with highest tensile strength has a low void ratio.

Table 2. PCPC properties from the literature

Void ratio (%)	Unit weight (lbs/ft3)	Permeability (in./hr)	28-day compressive strength (psi)	Flexural strength (psi)	Reference
United States					
15 to 25	100 to 125	288 to 756	800 to 3,000	150 to 550	Tennis et al. 2004
15 to 35	NA	NA	NA	363 to 566	Olek et al. 2003
International					
19	NA	NA	3771	638	Beeldens et al. 2003
20 to 30	118 to 130	NA	2553 to 4650	561 to 825	Beeldens 2001
NA	NA	NA	2756	NA	Tamai and Yoshida 2003
11 to 15	NA	36 to 252	NA	606 to 1,085	Kajio et al. 1998
18 to 31	NA	NA	1,595 to 3,626	NA	Park and Tia 2004

NA = not available

Strength

Since the aggregate strength is usually high, the strength of the thin paste around the aggregate particles and the strength of the interface between the aggregate and the paste are relatively weak. The pervious concrete strength therefore depends primarily on the properties of the paste and the interface between the paste and the aggregate (Yang and Jiang 2003). To improve the strength of pervious concrete, three components must be improved: the strength of the paste, the paste thickness around the aggregate, and the interface between the aggregate and the paste. These goals can be achieved by altering the mixing process, using smaller size aggregate, and/or using admixtures; all of these were used in the research presented in this report.

Strength is often the primary concern for concrete pavement designs. With a high void ratio (15%–35%) and often no fine aggregate, compressive, tensile, and flexural strengths tend to be lower than those of standard concrete (Beeldens et al. 2003). For low-volume pavement design of PCPC, the NRMCA suggests using a 28-day compressive strength and tensile strength of 2,500 psi and 500 psi, respectively (NRMCA 2004). For typical PCPC mixes used in the United States, the NRMCA reported a 28-day compressive strength ranging from 800 psi to 3,000 psi (Tennis et al. 2004). However, 3,000 psi is less than the compressive strength required for most conventional applications, typically 3,500 to 4,000 psi (Kosmatka et al. 2002). Hence, the use of PCPC has been limited primarily to parking lots (Tennis et al. 2004). Early mix designs used in the United States had flexural strengths ranging from 150 psi to 400 psi (Carolinas Ready Mixed Concrete Association Inc. 2003). Smaller aggregate was shown to produce higher flexural strength due to the increased contact area of the aggregate particles (Olek et al. 2003; Yang and Jiang 2003).

The relationship between flexural and split tensile strengths was investigated by Florida Concrete and Products Association Inc. (2000) and Beeldens et al. (2003). Florida Concrete and Products Association Inc. (2000) reported that split tensile strength is 65% of the flexural strength (Florida Concrete and Products Association Inc. 2000). However, Beeldens et al. (2003) reported that PCPC containing latex polymer may have a split tensile strength closer to 90% of the flexural strength.

Mixes used in Europe and Japan often incorporate aggregate smaller than that used in the United States, in addition to a small percentage of sand. These differences substantially increase strength values over domestic mixes. Some Belgian mix designs incorporating sand and a latex emulsion have produced a 28-day compressive strength of up to 4,600 psi. However, the permeability of this mix was not reported (Beeldens et al. 2003).

Porosity and Permeability

To facilitate the movement of water, interconnected voids must be present in the hardened pervious concrete. Higher porosity generally produces lower strength, while lower porosity mixes have higher strength. Ferguson (2005) and Tennis et al. (2004), reporting the properties of pervious concrete used in the United States, indicate a void ratio ranging from 14% to 31% and a coefficient of permeability ranging from 36 to 864 inches/hour. PCPC with void ratios between 15% and 25% produce strength values greater than 2,000 psi and a permeability of about 480 inches/hour (Tennis et al. 2004).

In all tests in which permeability values were reported, values were obtained using the falling head test adopted from soil mechanics. To produce higher flexural strength for a surface course, a void ratio of about 15% was used to yield a permeability of 14.4 inches/hour and a flexural strength of 650 psi (Kajio et al. 1998). PCPC with a void ratio above 20% has been shown to have a permeability of about 1,440 inches/hour, while void ratios of 20%–29% have resulted in flexural strengths of 400 psi to 500 psi (Olek et al. 2003).

Freeze-Thaw Durability

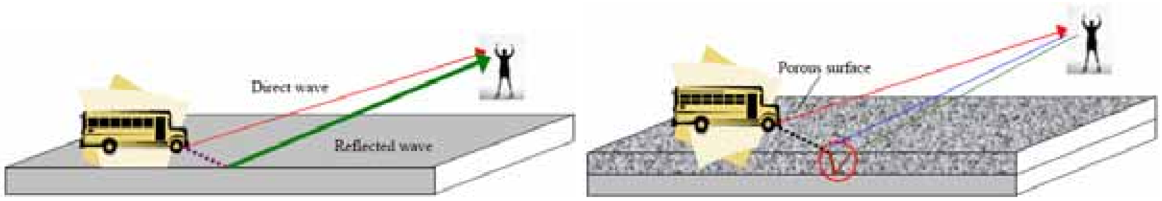
The primary obstacle preventing PCPC from being used in the cold regions of the United States is the lack of data and proper laboratory testing methods for verifying the durability of PCPC in freeze-thaw environments (NRMCA 2004). A number of methods exist that subject a sample to freezing and thawing cycles. The freeze-thaw test method most often reported involves freezing a sample in the dry condition and thawing it under water (ASTM C666B) or under more extreme conditions by freezing and thawing the sample in the fully saturated condition (ASTM C666A). These standard methods of evaluating freeze-thaw durability involve measuring the specimen's change in length and relative dynamic frequency (ASTM C215). It is difficult to apply these measurements, which were developed for normal concrete, to PCPC and produce consistent results. For example, the PCPC structure causes ambiguous determination of the fundamental frequency (Olek et al. 2003). For PCPC, the mass loss has been used as an indication of freeze-thaw durability. Yand and Jiang (2003) reported a mass loss of 0.25% after 25 cycles using ASTM C666 – Procedure B. The Belgian mixes containing latex were tested for 14 cycles using ASTM C666 – Procedure A and produced a relative tensile strength between 10% and 26%, which was measured by a direct tensile test (Beeldens 2001).

The rate of freeze-thaw cycles also affects the performance of PCPC. Results show that samples cycled five or six times per day deteriorate much faster than samples subjected to only one cycle per day. At 80 freeze-thaw cycles, the specimens that underwent the more rapid cycle rate had relative dynamic moduli of less than 40%, while their slower cycled counterparts had relative dynamic moduli greater than 90% (Olek et al. 2003).

Surface Characteristics

Noise Reduction

The open structure of the porous pavement causes a difference in arrival time between direct and reflected sound waves, as shown in Figure 2 (Olek et al. 2003). This difference decreases the noise level intensity, causing porous pavements to absorb the sound (Olek et al. 2003). This property has drawn the interest of many researchers to create quiet pavements (Kajio et al. 1998; Olek et al. 2003). Kajio et al. (1998) compared the noise levels produced from pervious concrete and dense asphalt pavements containing two different sizes of aggregate (1/4-inch and 1/2-inch) at different vehicle speeds.



(a) Wave reflection from a dense surface (b) Wave reflection from a porous surface

Figure 2. Reflection of sound waves resulting from moving vehicles

Table 3 (Kajio et al. 1998) shows that, for both sizes of aggregate, the noise level was reduced using pervious concrete. Small-size aggregate generally produced a quieter response, ranging from a 3% to 10% lower noise level, with a maximum difference of eight decibels (dB).

Olek et al. (2003) measured the noise reduction levels of PCPC using the tire-pavement test apparatus. PCPC was placed around a 12.1-foot diameter vertical drum. Once cured, a stationary vehicle tire made contact with the rotating drum. The tire was outfitted with an array of microphones to determine the average noise value of the pavement. Three mixes of PCPC were tested against three mixes of portland cement concrete. Two of the PCPC mixes were finished using a vibratory screed to smooth the surface, and the other was allowed to have random surface aggregate orientation. Frequency was measured at speeds of 10, 20, and 30 mph with a comparable trend in frequency for each speed. As the frequency increased, the PCPC became quieter than the standard concrete pavement, with a maximum of five decibels (dB) (Olek and Weiss 2003).

Table 3. Results of measurement of noise from pervious concrete slabs

Car	Pavement condition	Speed	Noise level (dB) Gradation 0.2 in.	Noise level (dB) Gradation 0.5 in.	Noise level (dB) Dense asphalt pavement
Normal	Dry	25 mph	65.8	66.6	72.3
		37 mph	72.2	74.5	79.9
		47 mph	75.1	77.9	82.5
	Wet	25 mph	66.8	68.1	70.6
		37 mph	73.1	74.4	77.2
		47 mph	75.9	77.8	80.4
Dump truck	Dry	25 mph	73.8	72.5	80.6
		37 mph	82.0	81.0	86.5
	Wet	25 mph	74.8	76.1	78.6
		37 mph	81.7	81.3	84.5

* Noise of idling dump truck = 60.0 db

Pervious Pavement Design

PCPC has been used as a surface layer on top of a standard concrete pavement or as a full-depth pavement layer (Beeldens et al. 2003; Ferguson 2005). At present, the focus in the United States is on full-depth design for parking lots and low-volume roads, while surface course designs are primarily used in Europe and Japan as a surface layer for roadways. Since PCPC does not necessarily behave like traditional PCC pavements, empirical designs have dominated construction practices (Tennis et al. 2004). When used as a surface layer on top of standard concrete pavement, a 1.5-inch layer of PCPC placed using a wet-on-wet method has produced a good bond between the PCPC and PCC, as well as a durable pavement (Beeldens et al. 2003). The wet-on-wet method places a thin layer of fresh PCPC over a thicker layer of fresh normal concrete.

Full-depth PCPC pavement sections consist of pervious pavement layers on top of a permeable subbase. Pavement thickness design can be calculated using standard design procedures. Since PCPC is susceptible to traffic loading deterioration due to its lower strength, daily truck traffic must be estimated accurately (Tennis et al. 2004). To account for its lower strength values, PCPC is typically 25% thicker than conventional concrete pavement (Carolinas Ready Mixed Concrete Association Inc. 2003). The minimum thickness for parking areas without truck traffic is 5 inches, which increases to 6 inches for industrial drive lanes in parking areas (Florida Concrete and Products Association Inc. 2000). The Florida PCPC design guide also provides thickness adjustments. A 0.12-inch increase or decrease in thickness may be made for every 25-psi change in the PCPC modulus of rupture. Also, a 2% decrease in void ratio requires an additional 1-inch of pavement depth to replace lost storage capacity (Florida Concrete and Products Association Inc. 2000).

The subbase material should be a clean, permeable material with a maximum size of up to 1.5 inches (Tennis et al. 2004; Florida Concrete and Products Association Inc. 2000). In most cases, the thickness of permeable subbase ranges from 6 inches to12 inches, although a subbase thickness of up to 24 inches is recommended in hard wet freeze areas (Tennis et al. 2004; NRMCA 2004). The thickness of subbase is often controlled by the permeability of the natural subgrade soil and the hydrologic loading to the pavement. Furthermore, NRMCA (2004) recommends that the groundwater table should not be within 3 feet of the bottom of the subbase so drainage is adequate.

The subgrade material should be a permeable soil that provides good support, with modulus of subgrade reaction k values ranging from 150 psi to 175 psi according to the Westergaard modulus method (Florida Concrete and Products Association Inc. 2000; Tennis et al. 2004). During construction, the natural subgrade must be protected from overcompaction to avoid creating an impermeable surface, unless additional mechanical drainage (e.g., a French drain) is installed.

Construction

In the United States, the most common method of PCPC placement is by hand, using forms. The PCPC is initially placed using a rear discharge concrete truck and then further placed by hand. Depending on the contractor’s experience, three methods can be used to compact the concrete. In the first method, a 1/2-inch to 3/4-inch spacer strip is placed on top of the forms, and the concrete is leveled using a vibratory screed, as shown in Figure 3 (Youngs 2005). Then, the spacer strip is removed and the surface is compacted using a smooth steel roller. The steel roller is also used in a transverse direction to finish the surface, as shown in Figure 4. The weight of the roller may vary, but 100 lbs per linear foot is common to produce the 10 psi of pressure suggested by the Carolinas Ready Mixed Concrete Association (CRMCA 2003). The second compaction method uses a vibratory plate compactor, which has only been used with mixes containing high-angularity aggregate (Youngs 2005). The third method of compaction and finishing uses a roller screed, as illustrated in Figure 5. The stainless steel pipe rotates in the opposite direction of the direction of movement.

Other less common methods of PCPC placement have been reported in the literature. These methods include high density paving machines, used in Tennessee to place full-depth PCPC pavement, and slip form pavers, used in Belgium to place a 1.5-inch surface coarse on top of a normal concrete layer (see Sparkman 2005; Beeldens et al. 2003).

Figure 3. Vibratory screed used in placing PCPC

Figure 4. Transverse steel roller over the moisture barrier

Figure 5. Compaction and finishing using a roller screed

In a manner similar to normal concrete, joints are used in PCPC to control and prevent random cracking. However, due to the rougher texture of PCPC, control joints are not always required. While most PCPC applications contain joints, a few parking lots in California have been placed without control joints (Youngs 2005). Since PCPC shrinks less than standard concrete, joint spacing larger than the standard 12 feet has been used. The NRMCA recommends slab lengths not exceeding 20 feet, although spacing of up to 45 feet has been reported to prevent shrinkage cracking (Paine 1992; Tennis et al. 2004). Joints can either be cut or formed, though formed joints are the preferred method because saw cut joints can cause raveling. A joint roller, often called a pizza cutter, quickly and easily forms PCPC joints, as shown in Figure 6 (Youngs 2005). Due to the large amount of exposed surface area, fresh PCPC must be sprayed with curing compound and covered with clear plastic sheeting soon after placement to prevent quick and excessive drying (Carolinas Ready Mixed Concrete Association Inc. 2003). Covered curing is recommended until the pavement is opened for operation, which should be a minimum of seven days after placement (Tennis et al. 2004).

Figure 6. Roller used to make joints in pervious concrete

Maintenance

PCPC must be properly maintained to prevent the surface from becoming clogged, which reduces permeability. Most PCPC sites function well without regular maintenance if protected from sand. Vacuuming or power blowing may be necessary if the site becomes clogged (Tennis et al. 2004). Pressure washing has shown to improve permeability of clogged pavement to 80%–90% of the original permeability (MCIA 2002). Many factors control how often maintenance must be performed on PCPC pavements. Generally, if the site is infiltrating large amounts of water or there are substantial amounts of fine soil from the surrounding areas, maintenance activities will be more frequent than if the pavement experiences lower hydraulic and solid loading. The chance of clogging is highest during and just after construction, and the site must be protected by an erosion control fence until vegetation has been established on the adjacent ground.

Environmental Issues

Stormwater Legislation

Due to recent amendments to the Clean Water Act (EPA 1999), municipalities must reduce the quantity of stormwater runoff and provide some amount of initial treatment. The United States Environment Protection Agency (EPA) regulates and monitors compliance with these regulations by granting NPDES permits. The new stormwater policy was implemented in two phases. In Phase I, NPDES permits required monitoring and treatment of stormwater by municipalities of 100,000 or greater, industrial discharges, and construction sites of five acres or more. In Phase II, NPDES permits increased accountability to municipalities greater than 10,000 people and construction sites greater than one acre (EPA 1996). In most cases, the individual state Departments of Natural Resources (DNRs) have been charged with enforcing the stricter standards.

Each phase has a set of performance standards that must be met and maintained before the NPDES permits are issued. These standards include reducing sediment loading by 80%, or to the maximum extent practicable. Furthermore, a target of 90% of pre-development infiltration or 25% of the 2-year, 24-hour storm event, with no more than 1% of the site dedicated to stormwater management, must be obtained. Exceptions will be allowed on a case by case basis as determined by the appropriate state DNR agency (Federal Register 2004).

To meet these performance standards, a set of best management practices (BMPs) have been suggested to help responsible parties meet the new standards. The BMPs are designed to facilitate stormwater detention, retention, infiltration, and treatment. In areas where a stormwater utility has been formed, the implementation of one or more BMPs results in a stormwater credit and savings to the owner. Porous pavements, such as PCPC, are approved BMPs and have a widespread use in areas that experience little to no freeze-thaw activity (EPA 2004).

A variety of other BMPs can be broadly grouped into two categories: structural and non-structural. The structural category encompasses any BMP that is installed or constructed. The commonly used structural treatment includes detention and retention ponds. Both reduce the amount and severity of storm events and provide treatment by allowing settling time for suspended contaminants. Furthermore, biofilters and wetlands are becoming more common as treatment methods, which are often installed in drainage swales. Non-structural BMPs are maintenance activities such as street sweeping and catch basin cleaning. Both reduce the amount of suspended solids released during the first flush (WERF 2005), which is the initial runoff from a storm event that contains the highest level of pollutants being flushed from the pavement. After the pavement has been cleaned of the first flush contaminants, the runoff becomes relatively free of pollutants. Many treatment methods require extra land area and additional construction, which increases overall construction costs. PCPC provides a convenient solution by incorporating the required BMP into a planned part of the pavement.

Hydrologic Effects

Pervious concrete performs two hydrologic tasks, stormwater storage and stormwater infiltration. Table 4 (Freeze and Cherry 1979) shows that most subgrade soil types have a limited infiltration rate. With a PCPC permeability higher than the subgrade soil's permeability, the subbase must be designed as a storage system to hold the stormwater until it can infiltrate into the subgrade. When the subgrade has limited permeability, additional drainage must be installed and connected to either the stormwater system or bio-retention areas, as shown in Figure 7 (Ferguson 2005). The depth of the subbase material is a function of the required storage capacity for the design storm rather than the structural capacity, unless freeze-thaw behavior is a concern. The time for complete infiltration should be as short as possible; the NRMCA limits this time to five days, while more standard designs suggest only holding water in the subbase for one or two days

(Huang 2004). The required 25% infiltration of the 2-year, 24-hour storm by NPDES represents a conservative estimate of the first flush, which can range in intensity from 1.5 inches to 6 inches across the United States, requiring PCPC pavement systems to hold 0.38 inches to 1.5 inches of stormwater (USDA 1986). For example, a 6-inch-thick layer of pervious concrete with 15% voids on top of an 8-inch-thick subbase with 40% voids would be able to hold 4.1 inches of stormwater, which is greater than the amount required for NPDES permits (Tennis et al. 2004).

Table 4. Range of soil permeability values

Soil type	Permeability (in./hr)
Gravel	> 144
Clean sand	7.2 to 1400
Silty sand	0.0144 to 144
Silt and loess	$1.44\text{x}10^{-4}$ to 1.44
Glacial till	$1.44\text{x}10^{-7}$ to 0.144

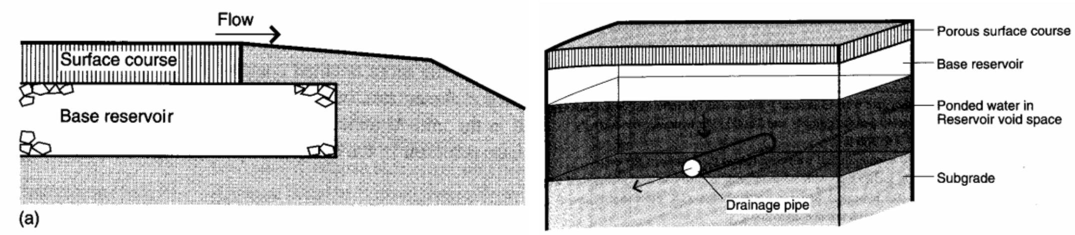


Figure 7. Cross-section of porous pavement systems with different drainage designs

Contaminant Reduction

In addition to reducing stormwater runoff, porous pavements have demonstrated the ability to treat water, both mechanically and biologically. Mechanical treatment is the entrapment of particles in the pavement structure or the sorption of contaminants onto the concrete or aggregate surfaces. Biological treatment is the degradation of contaminants by microorganisms attached to the pavement or in the soil beneath.

A study by Pratt et al. (1999) at the Coventry University School of Science and the Environment focused on the effect of hydrocarbon runoff, since permeable pavement had already been shown to retain suspended solids (Pratt et al. 1996). The one ft^2 test system was comprised of pervious concrete pavers placed on a pea gravel bed over a 15-inch crushed granite subbase. The pea gravel bed and crushed subbase have characteristics similar to those of PCPC systems. Motor oil, representing a volume that may drip from an automobile, was randomly deposited on a porous system. Runoff was then measured from simulated rainfall events and the results were compared with the results from normal concrete and asphalt test sections. Three rainfalls per week were simulated, with an intensity of 0.5 inches per hour for 28 minutes, yielding 0.28 inches of rain per simulated storm event. Oil was applied to the surface before each storm event. Over the course of the study, 0.32 liters of oil were applied to each section, and retention was measured by the difference between the oil concentration applied to the surface and the concentration in the runoff. The pervious pavement retained 99.6% of the oil, while standard concrete and asphalt retained only 70.2% and 49.6%, respectively.

The biological treatment capacity of pervious pavement was also evaluated by Pratt et al. (1999). The test specimens were seeded with microorganisms, and nutrient deficiencies were prevented by applying a slow-release, commercially available fertilizer. Oil was then applied as before and the effluent runoff concentration was measured, along with the respiration of the microorganisms. It was found that after 1,150 days, the runoff concentration of oil in the effluent remained negligible (Pratt et al. 1999).

A similar study performed at the University of Florida evaluated the effects of using PCPC for water purification (Park and Tia 2004). PCPC sections were submersed in a stream for three months to allow a microorganism population to become established. Water with known concentrations of chemicals was then passed through the seasoned PCPC sections, and the effluent concentration of total phosphorus and total nitrogen was measured. The maximum reduction was 47% for total nitrogen and 96% for total phosphorus (Park and Tia 2004). Table 5 (Schueler 1987) shows the values reported by the EPA to demonstrate the effectiveness of porous pavement systems. However, the pavement material type was not specified.

Table 5. Effectiveness of porous pavement pollutant removal, percent by mass

Study location	Total suspended solids	Total phosphorus	Total nitrogen
Prince William, VA	82	65	80
Rockville, MD	95	65	85

Key Findings from the Literature Review

- The increasing interest in pervious concrete is due to the recent Clean Water Act and other EPA regulations, which require decreasing the amount of water runoff and initial treatment of the runoff.
- The engineering properties reported in the literature from the United States indicate high void ratios, low strengths, and limited freeze-thaw test results for PCPC. It is believed that these limitations have hindered the use of pervious concrete in the hard wet freeze regions (e.g., the Midwestern and Northeastern United States).
- Typical mix design of pervious concrete used in the United States consists of cement, single-sized coarse aggregate (between 1-inch and the No. 4 sieve), and a water to cement ratio ranging from 0.27 to 0.43. The 28-day compressive strength of pervious concrete can range from 800 psi to 3,000 psi, with a void ratio ranging from 14% to 31% and a permeability ranging from 36 inches/hour to 864 inches/hour.
- The advantages of pervious concrete include improving skid resistance by removing water during precipitation events, reducing noise, minimizing the heat island effect in large cities, preserving native ecosystems, and minimizing costs in some cases.
- Full-depth and surface coarse PCPC pavement systems have been used, with the first being the most common in the United States and the second the most common in Europe and Japan.

- A typical cross-section of full-depth PCPC pavement consists of the following: (1) a pervious concrete layer with a thickness between 4 and 6 inches, (2) a permeable subbase with a thickness up to 18 inches, and (3) a permeable subgrade. If the subgrade permeability is low, drainage pipes can be used to drain water, though the pipes could increase the cost of the system.
- Studies have shown that pervious concrete has generally produced a quieter-than-normal concrete, with noise levels from 3% to 10% lower than those of normal concrete.
- Studies have indicated that pervious concrete has the ability to treat water, both mechanically and biologically.

MATERIALS, MIX PROPORTIONS, AND SPECIMEN PREPARATION

Materials

Aggregates Properties

Two types of single-sized coarse aggregate, crushed limestone and river gravel, were used in this study. Three sizes of single-sized river gravel were used: (1) 1/2-inch size with 100% passing the 5/8-inch and 100% retained on 1/2-inch sieve, (2) 3/8-inch size with 100% passing the 1/2-inch and 100% retained on the 3/8-inch sieve, and (3) No. 4 size with 100% passing the 3/8-inch and 100% retained on the No. 4 sieve. Additionally, single-sized 3/8-inch crushed limestone and two gradations of commercially available river gravel, known as pea gravel, were used. One gradation has 87% retained on the No. 4 sieve and 1.4% passing the No. 8 sieve with a uniformity coefficient of 1.73; the second has 33% retained on the 3/8-inch sieve, 60% retained on the No. 4 sieve, and 0.2% passing No. 8 sieve with a uniformity coefficient of 1.90 (see Figure 8).

The dry rodded unit weight, void ratio, specific gravity, and abrasion resistance of the aggregates were measured and are shown in Table 6. It can be seen that river gravel has a higher unit weight and abrasion resistance than crushed limestone. Table 6 includes two types of 3/8-inch–size crushed limestone because the properties of the aggregates obtained from the same source at an interval of six months had different engineering properties. The specific gravity and absorption were 2.62 and 1.1% for river gravel and pea gravel, 2.45 and 3.2% for the first crushed limestone (LS1), and 2.55 and 3.2% for the second crushed limestone (LS2), respectively.

To improve the strength of single-sized coarse aggregate mixes, concrete river sand, latex, and silica fume were used. The sand has 90% passing the No. 8 sieve (see Figure 8), a fineness modulus of 2.9, a specific gravity of 2.62, and an absorption of 1.1%.

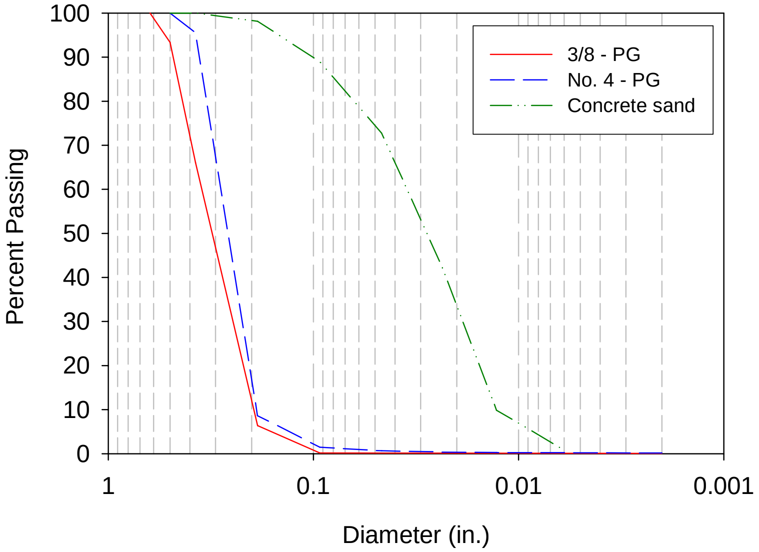


Figure 8. Gradation of pea gravel and concrete sand

Table 6. Properties of aggregates used in the pervious concrete mixes

Aggregate size and type	River gravel			Crushed limestone		Pea gravel	
	1/2 inch	*3/8 inch*	*No. 4*	*3/8 inch†*	*3/8 inch**	*3/8 inch*	*No. 4*
Unit weight (lbs/ft^3)	100.0	102.6	99.6	86.5	88.8	102.6	104.3
Voids (%)	38.8	37.3	38.5	43.5	44.2	37.2	36.2
Abrasion mass loss (%)	14.4	14.4	14.4	46.1	32.9	13.7	10.8
Specific gravity	2.62	2.62	2.62	2.45	2.55	2.62	2.62
Absorption	1.1	1.1	1.1	3.2	3.2	1.1	1.1

†Denotes LS1 * Denotes LS2

Cementitious Material Properties

A Type I/II cement from La Farge, USA was used in all prepared mixes. Table 7 lists the cement properties given in the material property report provided by the manufacturer.

Table 7. Physical properties and chemical analysis of cement

Physical tests	
Fineness-Blaine	1,878 ft^2/lbs
Specific gravity	3.15
Vicat setting time	90 min.
Compressive strength	
7-day	4,460 psi
28-day	6,300 psi
Autoclave expansion	0.02 %
Chemical analysis wt. %	
Silicon Dioxide (SiO_2)	20.5
Aluminum Oxide (AL_2O_3)	4.2
Ferric Oxide (Fe_2O_3)	3.3
Calcium Oxide (CaO)	62.3
Magnesium Oxide (MgO)	2.9
Sulfur Trioxide (SO_3)	3.0
Loss on ignition	1.2
Insoluble residue	0.23
Free lime	1.0
Tricalcium Silicate (C_3S)	57
Tricalcium Aluminate (C_3A)	6
Total Alkali as NaEq	0.53

A densified silica fume from Degussa, USA was used at 5% binder replacement to improve strength and bonding characteristics of selected mixes. The specific gravity is 2.2, with a bulk density of 30–40 lbs/ft^3 given in the material property report provided by the manufacturer.

Admixture Properties

A styrene butadiene rubber (SBR) latex was used to improve the cement-aggregate bond and the freeze-thaw durability. The SBR latex has been approved by the Federal Highway Administration for latex-modified concrete used in bridge deck overlays (Dow 2005). Air entraining agent (AEA) and high-range water reducer (HRWR) were mainly used in the mixes that did not contain latex. Table 8 lists the properties of the SBR latex, and Table 9 lists the properties of AEA and HRWR.

Table 8. Latex polymer characteristics

Chemical family	Styrene butadiene polymer
Chemical name	Dow Chemical-Modifier A/NA
Concentration (by mass)	Nonvolatile content 47%–49%
Appearance	Milky white liquid emulsion
Odor	Slight odor
Viscosity	40 cPs (max)
pH	9.0-11.0
Min. film forming temperature	39.2°F
Polymer particle size	190-220 nm
Density	63.6 lbs/ft^3

Table 9. Admixture characteristics

Name	Type	Color	Specific gravity	pH
Glenium 3400 NV	High-range water reducing admixture	Dark brown	1.07	7.8
Everair Plus	Air-entraining agent	Brown	1.01	10

Mix Proportions

General Information

The mix design was conducted in two phases. Phase I investigated how aggregate size and type influenced the void ratio and strength of pervious concrete, and Phase II investigated the effects of sand, latex, and silica fume on pervious concrete properties. The proportions of all prepared mixes are summarized in Table 10. Mix identification begins with a number that indicates the size of the aggregate. Following the number are two letters indicating the aggregate type, and then either S for sand, L for latex, or SF for silica fume. The numbers following these letters indicate the percent of the material used in the mix.

The binder to aggregate ratio varied from 0.20 to 0.24, with a ratio of 0.21 found to provide the best particle coverage without excess cement paste. The effects of the percentage of latex on the pervious concrete's workability, strength, and water reduction were initially investigated to determine the optimum percentage used in all other mixes.

Specimen Preparation

Initial samples were prepared with single-sized 3/8-inch river gravel using the traditional concrete mixing procedure, in which aggregate, water, and admixtures are mixed before the addition of cement. Using this mixing procedure, it was observed that the samples, when subjected to compression, failed at the interface between the cement paste and the aggregate. This failure is indicated by the exposed intact aggregate at the failure surface, as shown in Figure 9a. Therefore, a second mixing procedure was conducted to improve the bond between the cement paste and the aggregate by dry mixing a small amount of cement (<5% by mass) with the aggregate until completely coated (about one minute). Next, the remaining cement and water (with or without HRWR) was added. Finally, the concrete was mixed for three minutes, allowed to rest for three minutes, and then mixed for an additional two minutes before casting. Samples produced from this modified mixing procedure failed through the aggregate (see Figure 9b), which increased the compressive strength of the mix. The limestone mixes showed no significant increase in strength due to the textured nature of the limestone.

(a) Mixing procedure 1 (b) Mixing procedure 2

Figure 9. Failure surface of sample mixes using the two mixing procedures

All cylindrical specimens were placed by rodding 25 times in three layers while applying a vibration for five seconds after rodding each layer. The samples were then demolded after 24 hours, placed in a fog room at 98% relative humidity, and cured according to ASTM C192. Before compression testing, the cylinders were capped using a sulfur capping compound, according to ASTM C617. To vibrate the samples, two vibrating tables with amplitudes of 0.005-inches and 0.0034-inches, which were identified as regular and low compaction energies, respectively, were used initially to investigate the effect of compaction energy on PCPC properties.

Cylinders 4 inches in diameter and 8 inches in length were used for both compression and tensile strength tests. Cylinders with a diameter of 3 inches and a length of 6 inches were used to determine the void ratio, and cylinders 3 inches in diameter and 3 inches in length were used to measure permeability. Beams with a cross-section of 3 inches by 3 inches and a length of 16 inches were used for the freeze-thaw tests.

Table 10. Phase I and II mix proportions

					Binder								
	Mix number	Compct. lvl. ***	Agg. type	Agg. size	Cement (lb/yd^3)	Latex (lb/yd^3)	Silica fume (lb/yd^3)	Agg. (lbs/yd^3)	Sand (lbs/yd^3)	Water (lbs/yd^3)	AEA (oz/100 lb PC)	HRWR (oz/100 lb PC)	water/ cementitious
Phase I	No. 4-RG	Reg.	RG	No. 4	578	-	-	2700	-	156.1	2.15	4.25	0.27
	3/8-RG	Reg.	RG	3/8"	600	-	-	2700	-	162	2.15	4.25	0.27
	1/2-RG	Reg.	RG	1/2"	550	-	-	2700	-	148.5	2.15	4.25	0.27
	3/8-LS	Reg.	LS	3/8"	578	-	-	2700	-	156.1	2.15	4.25	0.27
Phase II	No. 4-RG-S7	Reg.	RG	No. 4	571	-	-	2500	168	154.2	2.15	4.25	0.27
	No. 4-RG-L10	Reg.	RG	No. 4	525	52.5	-	2700	-	115.5	-	-	0.22
	No. 4-RG-L5	Reg.	RG	No. 4	542.5	28.6	-	2500	168	157.3	-	-	0.29
	No. 4-RG-S7-L10	Reg.	RG	No. 4	520	52	-	2500	168	114.4	-	-	0.22
	No. 4-RG-S7-L10	Low	RG	No. 5	520	52	-	2500	168	114.4	2.15	-	0.22
	No. 4-RG-S7-L15	Reg.	RG	No. 4	485.4	85.7	-	2500	168	106.8	-	-	0.22
	3/8-RG-S7	Low	RG	3/8"	571	-	-	2500	168	154.2	2.15	4.25	0.27
	3/8-RG-S7	Reg.	RG	3/8"	571	-	-	2500	168	154.2	-	4.25	0.27
	3/8-RG-SF5	Reg.	RG	3/8"	522.5	-	27.5	2700	-	141.1	2.15	4.25	0.27
	3/8-RG-S7-L10	Reg.	RG	3/8"	520	52	-	2500	168	114.4	-	-	0.22
	1/2-RG-SF5	Reg.	RG	1/2"	522.5	-	27.5	2700	-	141.1	2.15	4.25	0.27
	3/8-LS-S7	Low	LS	3/8"	571	-	-	2500	168	154.2	2.15	4.25	0.27
	3/8-LS-S7	Reg.	LS	3/8"	571	-	-	2500	168	154.2	2.15	4.25	0.27
	3/8-LS-SF5	Reg.	LS	3/8"	522.5	-	27.5	2700	-	141.1	2.15	4.25	0.27
	3/8-LS-S7-L10	Low	LS	3/8"	571	57.1	-	2500	168	125.6	-	-	0.22
	3/8-LS-S7-L10	Reg.	LS	3/8"	571	57.1	-	2500	168	125.6	-	-	0.22
	3/8-PG	Reg.	PG	3/8"	578	-	-	2700	-	156.1	2.15	4.25	0.27
	No. 4-PG	Low	PG	No. 4	578	-	-	2700	-	156.1	2.15	4.25	0.27
	No. 4-PG	Reg.	PG	No. 5	578	-	-	2700	-	156.1	2.15	4.25	0.27
	No. 4-PG-L10	Low	PG	No. 4	525	52.5	-	2700	-	115.5	2.15	4.25	0.22

RG: River Gravel, LS: Limestone, PG: Pea Gravel

*Latex solids not considered a cementitious material

**Sand is included in the gradation of pea gravel

***Regular indicates 0.005 inch vibration amplitude and Low indicate 0.0034 inch vibration amplitude

Summary of Materials, Specimen Preparation, and Mix Proportions

- Singled-sized coarse aggregate, river gravel (No.4, 3/8-inch, and 1/2-inch), and crushed Limestone (3/8-inch) were used in PCPC mixes.
- Two pea gravel gradations were used in this study: (1) No. 4-PG, which has 87% retained on the No. 4 and 1.4% passing the No. 8 sieve; and (2) 3/8-PG, which has 33% retained on the 3/8-inch, 60% retained on the No. 4, and 0.2% passing the No. 8 sieve.
- Three binding materials were used in this research: cement, silica fume, and a latex polymer.
- A modified mixing procedure, where 5% cement content was dry-mixed with the aggregate, improved the paste-aggregate bond and mix strength.
- The cement content used in the prepared mixes was varied to reduce excess paste content. A binder to aggregate ratio of 0.21 was found to provide particle coverage with no excess cement.
- Standard concrete sand with a fineness modulus of 2.9 was used in a number of mixes at a ratio of 7% sand to coarse aggregate.

TESTING PROCEDURES

A number of standard tests were conducted to characterize the PCPC mix properties, including slump, void ratio, permeability, unconfined compressive strength, split tensile strength, and freeze-thaw tests. The methods and calculations used in these tests are summarized below.

Workability of fresh concrete was determined by a standard slump cone test following ASTM C143. Compressive strength tests were performed according to ASTM C39, and splitting tensile tests were performed according to ASTM C496.

The void ratio of pervious concrete was determined by calculating the difference in weight between the oven dry sample and the saturated under water sample and using Equation 1 (Park and Tia 2004).

$$\mathrm{V_r} = [1-(\frac{\mathrm{W_2}-\mathrm{W_1}}{\rho_{\mathrm{w}}\mathrm{Vol}})]100(\%) \qquad (1)$$

Where,

V_r = total void ratio, %
W_1 = weight under water, F
W_2 = oven dry weight, F
Vol = volume of sample, L^3
ρ_w = density of water, F/L^3

The permeability of the samples was determined using the falling head permeability test apparatus illustrated in Figure 10. A flexible sealing gum was used around the top perimeter of the sample to inhibit water leakage along the sides of the sample. The samples were then confined in a membrane and sealed in a rubber sleeve, which was surrounded by adjustable hose clamps. The test was performed using several water heights, which represented values that a pavement may experience in practice. The average coefficient of permeability (k) was determined using Equation 2 (see Das 1998).

$$k = \frac{aL}{At} LN\left(\frac{h_1}{h_2}\right) \qquad (2)$$

Where,

k= coefficient of permeability, L/T
a = cross-sectional area of the standpipe, L^2
L = length of sample, L
A = cross-sectional area of specimen, L^2
t = time for water to drop from h_1 to h_2, T
h_1 = initial water level, L
h_2 = finial water level, L

Selected mixes with an adequate void ratio and seven-day compressive strength were further investigated using strength tests as a function of time and freeze-thaw resistance according to ASTM C666, procedure A, in which samples were frozen and thawed in saturated conditions. The test was completed when the sample reached 300 cycles or 15% mass loss, which was determined to represent a terminal serviceability level. Due to the change in crushed limestone properties described in the Aggregate Properties section of this report, and although the tests were performed on PCPC mixes with limestone aggregate, the freeze-thaw results presented in this report focus on the performance of pervious concrete made using No. 4 river gravel and 3/8-inch river gravel, which showed high seven-day compressive strength and adequate permeability.

In addition, X-ray computed tomography scanning (CT scanning) was conducted on selected initial samples to obtain views of the void continuity. The testing methods used are discussed in the Appendix.

Figure 10. Permeameter used to measure the permeability of pervious concrete samples

Summary of Testing Procedures

- Compressive strength was tested at 7 days for all mixes and at 21 days and 28 days for selected mixes.
- Split tensile strength was tested at 28 days for selected mixes.
- Permeability was measured using a falling head permeameter at representative water levels.
- Saturated freeze-thaw testing was performed on selected mixes for 300 cycles or up to a 15% mass loss.

RESULTS

Effect of Aggregate Type and Size

The slump of all mixes ranges from 0 to 0.5 inches. The void ratio of a mix is a function of many factors, including compaction energy, sand content, and type and size of aggregate used in the mix. For the river gravel mixes, it was found that the average PCPC void ratios tend to increase as the aggregate size increases (see Figure 11), with a lower void ratio when sand is in the mix.

The pea gravel used in mix 3/8-PG had the highest seven-day compressive strength (4,027 psi) and the lowest void ratio (11.2%) and coefficient of permeability (14.4 inches/hour). Mix No. 4-PG had the lowest strength of the mixes that used pea gravel, with a seven-day strength of 2,526 psi, a void ratio of 20.9%, and a coefficient of permeability of 468 inches/hour.

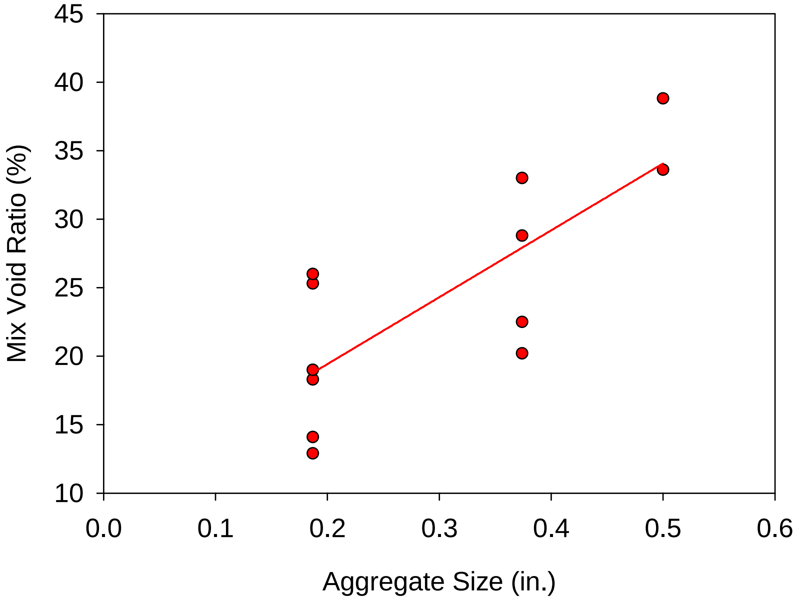


Figure 11. Relationship between river gravel aggregate size and PCPC void ratio

The abrasion test results reported in Table 11 show that river gravel has higher abrasion resistance (which also indicates aggregate strength) than crushed limestone. The effects of aggregate properties on the mix properties can be illustrated by comparing mixes No. 4-RG and 3/8-LS, which have the same mix proportions but different aggregate types. Mix No. 4-RG has a higher seven-day compressive strength than mix 3/8-LS (2,100 psi vs. 1,396 psi, respectively).

Table 11. Engineering properties of PCPC mixes

Mix*	Compact. level**	Unit weight (lbs/ft3)	Void ratio (%)	Compressive strength (psi)			Split strength (psi)	Permeability (in./sec.)
				7-day	21-day	28-day		
No. 4-RG	Regular	117.5	25.3	2100	2385	2506	287	0.10
3/8-RG	Regular	116.9	28.8	1771	-	-	-	-
1/2-RG	Regular	112.9	38.8	1145	-	-	-	-
3/8-LS	Regular	104.1	33.6	1396	1663	1722	205	0.57
No. 4-RG-S7	Regular	127.7	18.3	3299	3380	3661	429	0.04
No. 4-RG-L10	Regular	135.2	12.9	3142	-	-	-	-
No. 4-RG-L5	Regular	120.3	26.0	1307	-	-	-	-
No. 4-RG-S7-L10	Regular	126.8	19.0	2969	3313	3349	453	0.07
No. 4-RG-S7-L10	Low	123.0	23.2	1737	1848	1960	197	0.26
No. 4-RG-S7-L15	Regular	132.2	14.1	2735	-	-	-	0.02
3/8-RG-S7	Low	121.6	22.5	2725	2735	2830	301	0.13
3/8-RG-S7	Regular	130.9	20.5	3262	-	-	-	0.19
3/8-RG-SF5	Regular	111.6	33.0	1347	-	-	-	-
3/8-RG-S7-L10	Regular	127.3	20.2	2641	-	2924	-	0.09
1/2-RG-SF5	Regular	110.5	33.6	1313	-	-	-	-
3/8-LS-S7	Low	107.8	33.2	1504	2024	2096	203	0.59
3/8-LS-S7	Regular	119.8	23.0	3229	-	-	-	0.09
3/8-LS-SF5	Regular	98.6	41.8	784	-	-	-	-
3/8-LS-S7-L10	Low	111.3	28.8	1796	1870	2045	201	0.25
3/8-LS-S7-L10	Regular	117.4	25.7	2483	-	-	-	0.19
3/8-PG	Regular	138.9	11.2	4027	-	-	-	0.004
No. 4-PG	Low	125.2	20.9	2526	2963	3113	249	0.13
No. 4-PG	Regular	125.3	22.6	2773	-	-	-	0.13
No. 4-PG-L10	Low	122.9	22.9	2099	2426	2452	231	0.28

*Mix Names: N-X-YJ

N = is the aggregate size which indicate the size of the sieve on which 100% of the aggregate is retained on

X = RG for River Gravel, LS for Limestone, PG for Pea Gravel

Y: S for Sand with J%, L for Latex with L%, SF for Silica Fume with M%

**Regular compaction indicates using a vibrating table with 0.005 inch amplitude and Low compaction indicate using a vibrating table with 0.0034 inch amplitude

Effect of Sand, Latex, and Silica Fume

The results of Phase I (see Table 11) indicate that the void ratio of mixes 4-RG, 3/8-RG, 1/2-RG, and 3/8-LS were all greater than 25%, and the seven-day compressive strength ranged from 1,393 psi to 2,100 psi. Among the four mixes, 3/8-LS had the highest void ratio and the lowest compressive strength; however, 4-RG had the highest strength and the lowest void ratio.
For Phase II test results, mixes 3/8-PG and No. 4-RG-S7 had the highest compressive strength.

The mixes that show the maximum compressive strength for both river gravel and crushed limestone are those that include sand and no latex. No. 4-RG-S7 had a 28-day compressive strength of 3,661 psi, and mix 3/8-LS-S7 had a compressive strength of 2,096 psi.

The effect of using sand in pervious concrete mixes placed using regular compaction energy was investigated by replacing 7% by weight of the coarse aggregate with fine sand. When comparing mixes No. 4-RG, 3/8-RG, and 3/8-LS to mixes No. 4-RG-S7, 3/8-RG-S7, and 3/8-LS-S7, the seven-day compressive strength increases by 57%, 54%, and 8%, and the void ratio decreases by 7%, 6%, and 0.4%, respectively. However, the permeability of mix No. 4-RG-S7 was 60% less than mix No. 4-RG (141.7 inches/hour and 354 inches/hour, respectively). Nevertheless, the measured permeability for this mix was much higher than the maximum permeability required to drain the maximum 25-year, 24-hour storm across the United States (i.e., 12 inches), as discussed in the literature review.

Crushed limestone LS1 and LS2 were used to prepare mixes 3/8-LS and 3/8-LS-S7, respectively. In comparing the aggregate properties of the crushed limestone used in these two mixes, which were placed using the same compaction energy, it was concluded that the strength increase may have been influenced by the change in aggregate properties as described in the Aggregate Properties section of this report.

When latex was added to mix No. 4-RG (in mix No. 4-RG-L10), the seven-day compressive strength was improved by 50% and the void ratio was reduced by 12.4%. When both latex and sand were used in No. 4-RG-S7-L10 with regular compaction energy, the increase in seven-day compressive strength was less than that achieved using only sand or latex. However, the permeability increased from 144 inches/hour to 252 inches/hour. Furthermore, mixes No. 4-RG-L10 and No. 4-RG-S7-L10, placed with regular compaction energy, showed an increase of 49% and 58% in split strength, respectively, over mix No. 4-RG (429 psi and 453 psi vs. 287 psi).

Silica fume was added at 5% replacement of cement by mass to improve the cement paste strength. When added to mix 3/8-RG (in mix 3/8-RG-SF5), the seven-day compressive strength of the samples decreased by 24% and the void ratio increased by 4.2%. When silica fume was added to mix 3/8-LS to prepare mix 3/8-LS-SF5, the seven-day compressive strength decreased by 44% while the void ratio increased by 8.2%. It is estimated that this decrease in strength was due to an increase in the mix void ratio caused by the silica fume. No additional tests were conducted because of this strength decrease.

Void Ratio and Compressive Strength Trends

The development of compressive strength as a function of time is shown in Figure 12 for three mixes with No. 4 river gravel, two mixes with 3/8-inch river gravel, three mixes with 3/8-inch crushed limestone, and two mixes with No. 4 pea gravel. The general trend is an increase in strength as a function of time, with the highest strength gain in the first seven days. When comparing mixes No. 4-RG-S7 and No. 4-PG with mixes No. 4-RG-S7-L10 and No. 4-PG-L10, it was observed that using latex hindered strength improvement between the 21st and 28th days.

For all mixes prepared using regular compaction energy, the compressive strength of pervious concrete decreased linearly as the void ratio increased (see Figure 13). For both river gravel and crushed limestone, the decrease in strength as a function of void ratio is also linear (see Figures 14 and 15). At regular compaction effort, the seven-day compressive strength projected to zero void ratio for mixes with limestone is greater than that for mixes with river gravel (5,874 psi vs. 4,745 psi). However, limestone mixes show a greater decrease in strength as the void ratio increases (125.7 psi vs. 100.5 psi per each percent of void ratio change).

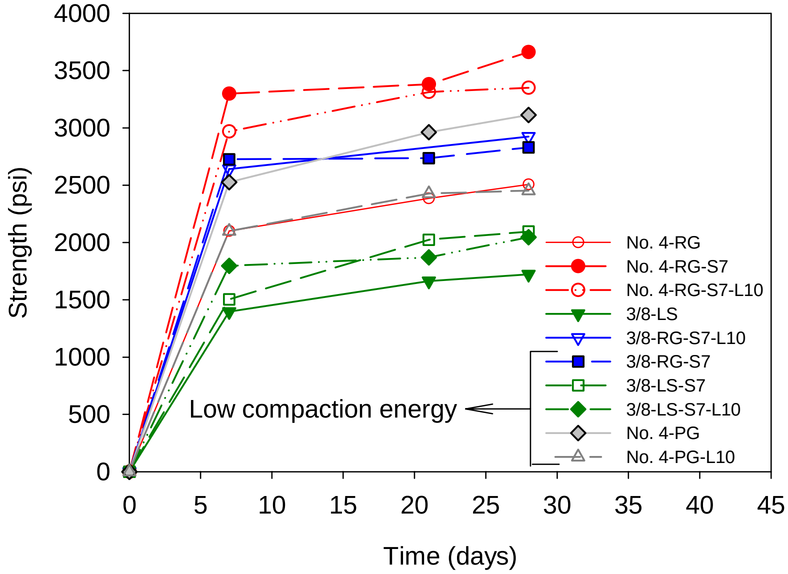


Figure 12. Strength development with time

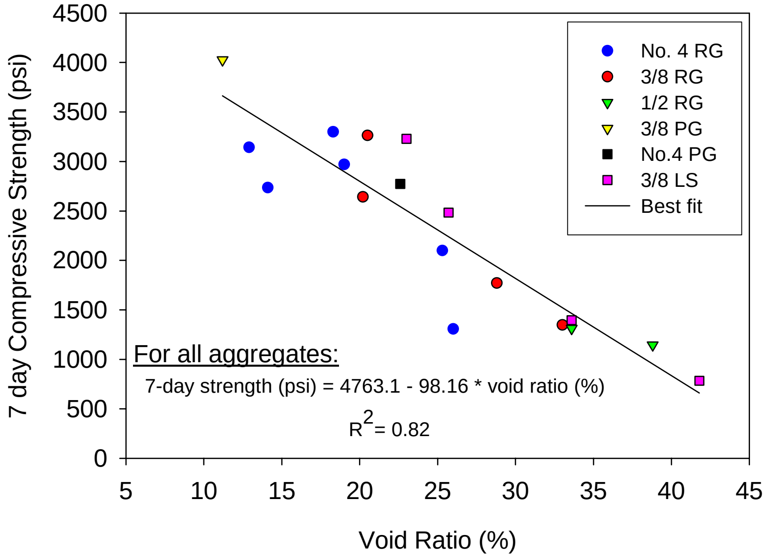


Figure 13. Relationship between void ratio and seven-day compressive strength for all mixes placed using regular compaction energy

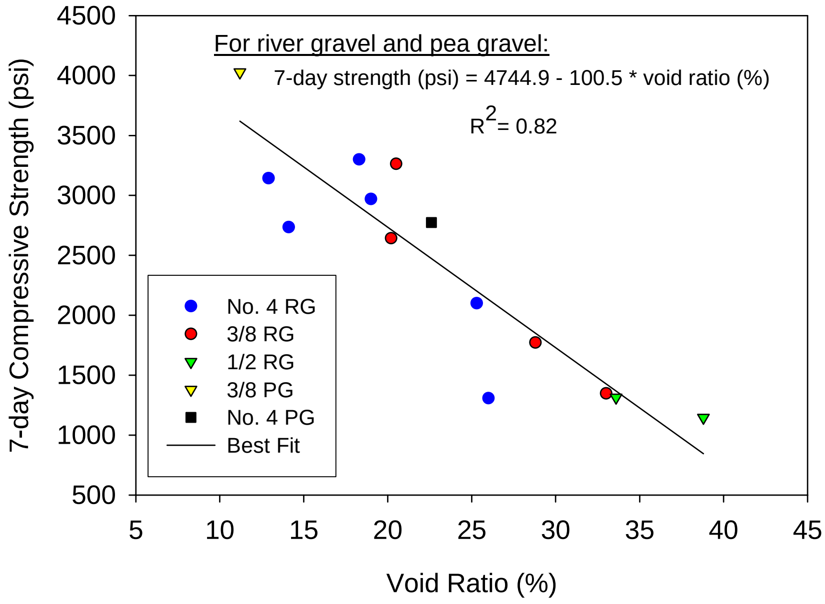


Figure 14. Relationship between void ratio and seven-day compressive strength for river gravel and pea gravel mixes placed using regular compaction energy

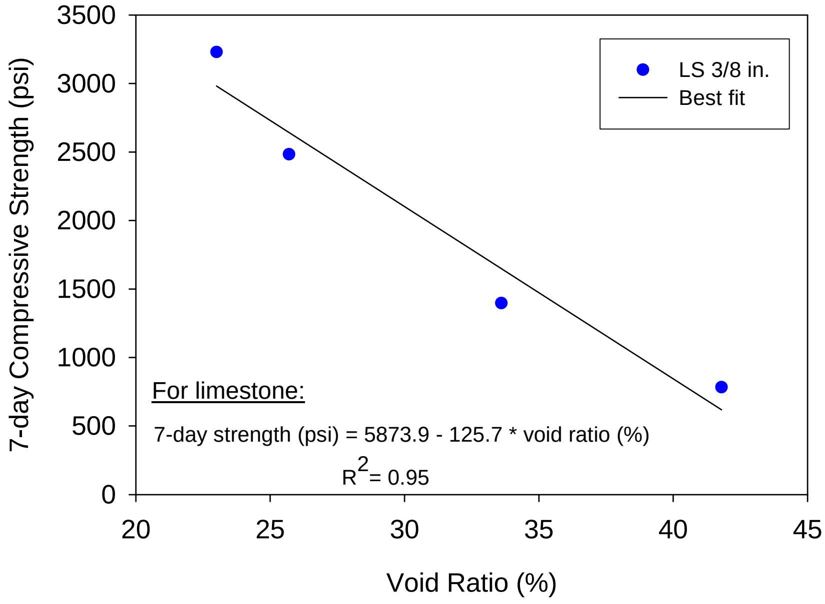


Figure 15. Relationship between void ratio and seven-day compressive strength for limestone mixes placed using regular compaction energy

Figure 16 shows the relationship between the 28-day compressive strength and 28-day split strength of pervious concrete for mixes placed using regular compaction energy. This relationship is linear, with the split strength equal to about 12.3% of the compressive strength.

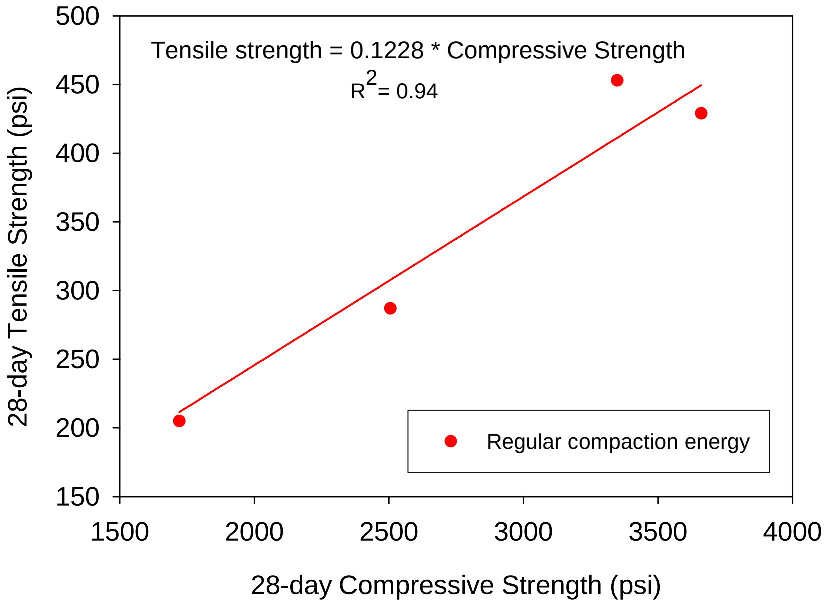


Figure 16. Relationship between 28-day compressive strength and 28-day split strength

The unit weight for all mixes prepared using regular compaction energy decreases linearly as a function of void ratio. Figure 17 shows the relationship between unit weight and void ratio, where mixes with the lowest void ratios had the highest unit weights, and, oppositely, mixes with the highest void ratios had the lowest unit weights.

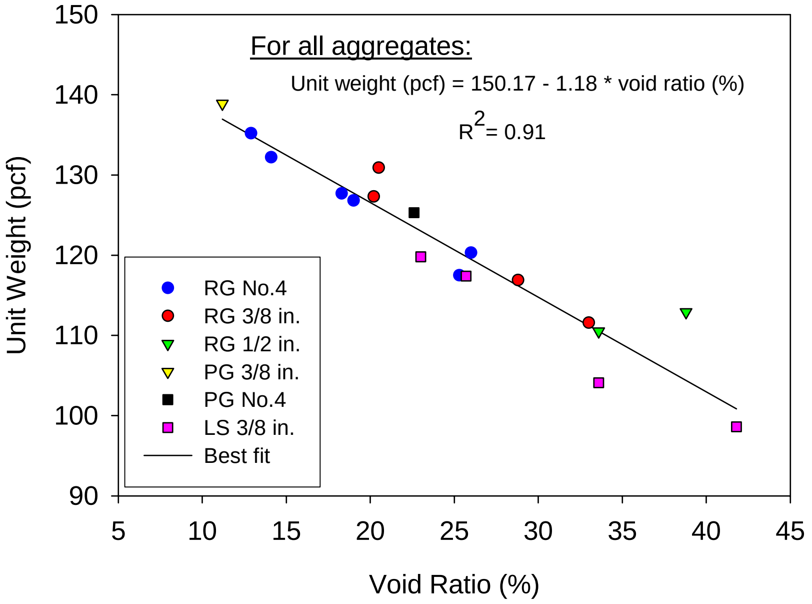


Figure 17. Relationship between unit weight and void ratio for all mixes placed using regular compaction energy

Void Ratio and Permeability Trends

Figure 18 shows that the coefficient of permeability of PCPC mixes increases exponentially as a function of void ratio, with the permeability rapidly increasing for voids greater than 25%. For all mixes, the coefficient of permeability ranges from 14 inches/hour to 2,050 inches/hour. Figure 19 shows that as the permeability increases as a function of void ratio, the strength linearly decreases. Mixes with a void ratio between 15% and 19% achieve both an adequate seven-day compressive strength of about 3,000 psi or more and a permeability between 135 inches/hour and 240 inches/hour, indicated in Figure 19 as the limits of the target region. It has been observed that mixes that achieve both the required strength and adequate permeability have a unit weight ranging from 127 pcf to 132 lbs/ft^3. This value of the pervious concrete unit weight could be used as a quick quality control/quality assurance indicator at the time of placing pervious concrete.

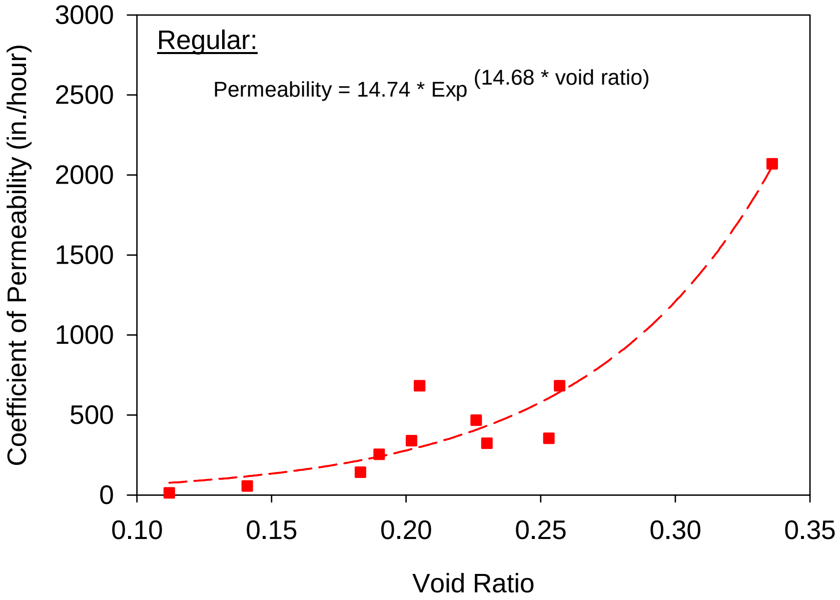


Figure 18. Relationship between pervious concrete void ratio and permeability for all mixes placed using regular compaction energy

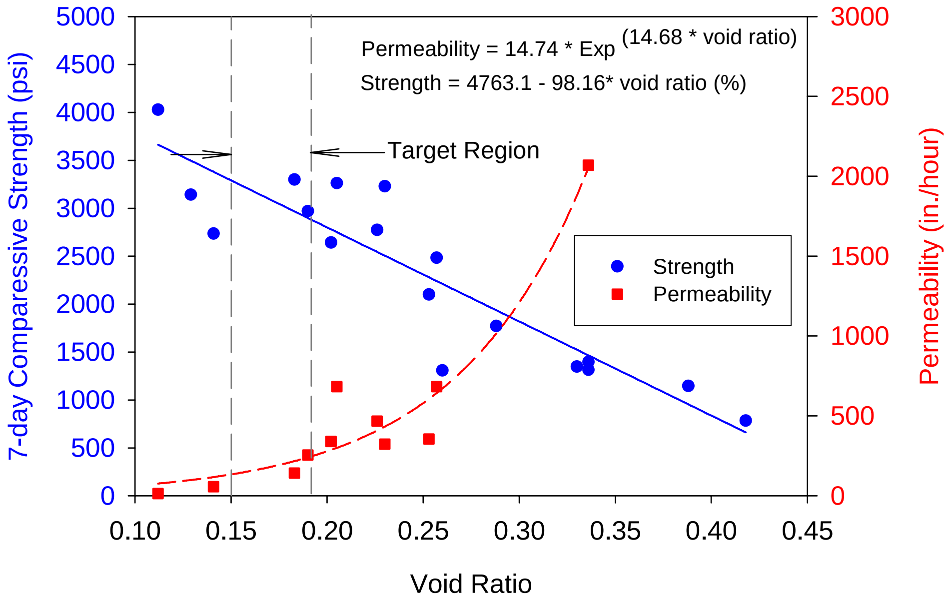


Figure 19. Relationship between pervious concrete void ratio, permeability, and seven-day compressive strength for all mixes placed using regular compaction energy

Effect of Compaction

PCPC properties were evaluated using two levels of compaction energy, regular and low. Regular compaction energy represents a vibration table with an amplitude of 0.005 inches, while low compaction energy represents a vibration table with amplitude of 0.0034 inches, which is 68% of the regular compaction energy.

Table 12 summarizes the test results of three identical mixes compacted using regular and low compaction energies. These results show that using low compaction energy resulted in reduced unit weight, increased void ratio, increased permeability, and reduced compressive strength.

The effects of compaction energy on the trends of compressive strength, split strength, unit weight, and permeability are presented in Figures 20, 21, 22, and 23. These results indicate that compaction affects PCPC properties by reducing compressive strength, split strength, and unit weight and by increasing permeability. For example, Figure 20 shows that the average seven-day compressive strength at a 22% void ratio decreases from 2,603 psi to 2,315 psi, which represents an 11% reduction. Figure 21 shows that the split strength decreases from about 12.3% to about 9.5% of the compressive strength as the compaction energy decreases from regular energy to low energy. Figure 23 indicates that the average permeability of PCPC at a void ratio of 22% increases from 372 inches/hour to 614 inches/hour, which represents a 65% increase. The effect of compaction using other compaction energies and larger number of samples is recommended for future research.

Table 12. Effect of compaction energy on pervious concrete material properties

Mix	Compaction energy	Unit weight (lbs/ft^3)	Void ratio (%)	Seven-day compressive strength (psi)	Permeability (in./hr)
No. 4-RG-S7-L10	Regular	126.8	19	2,969	252
No. 4-RG-S7-L10	low	123	23.2	1,737	936
3/8-LS-S7	Regular	119.8	23	3,229	324
3/8-LS-S7	low	107.8	33.2	1,504	2124
3/8-LS-S7-L10	Regular	117.4	25.7	2,483	684
3/8-LS-S7-L10	low	111.3	28.8	1,796	900

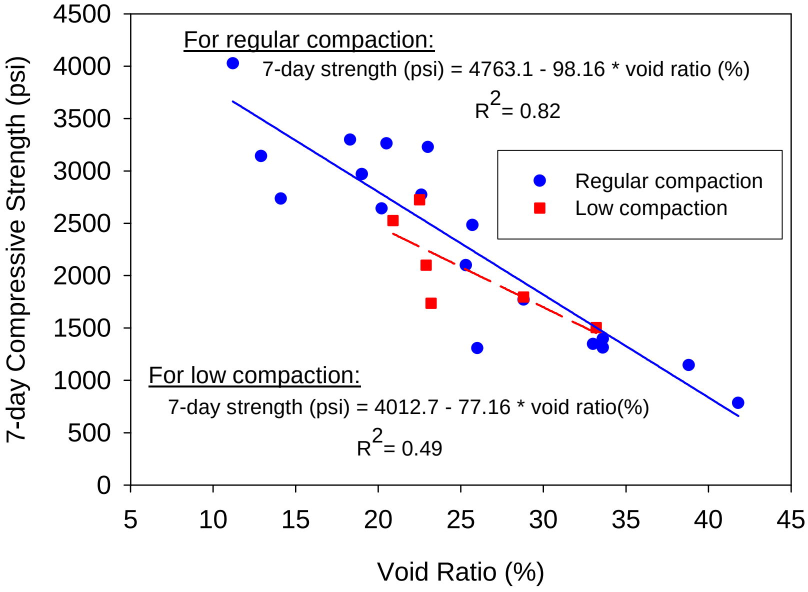


Figure 20. Effect of compaction energy on seven-day compressive strength for all aggregates used

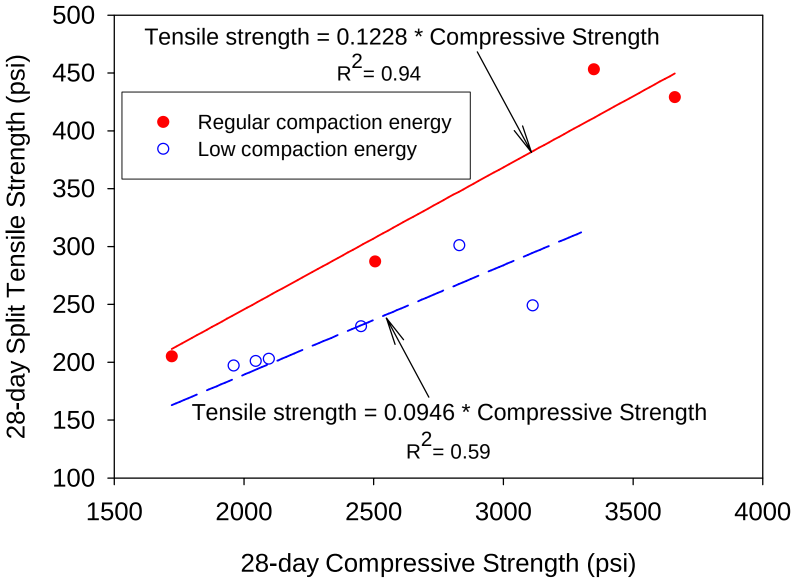


Figure 21. Effect of compaction energy on the relationship between compressive strength and split strength

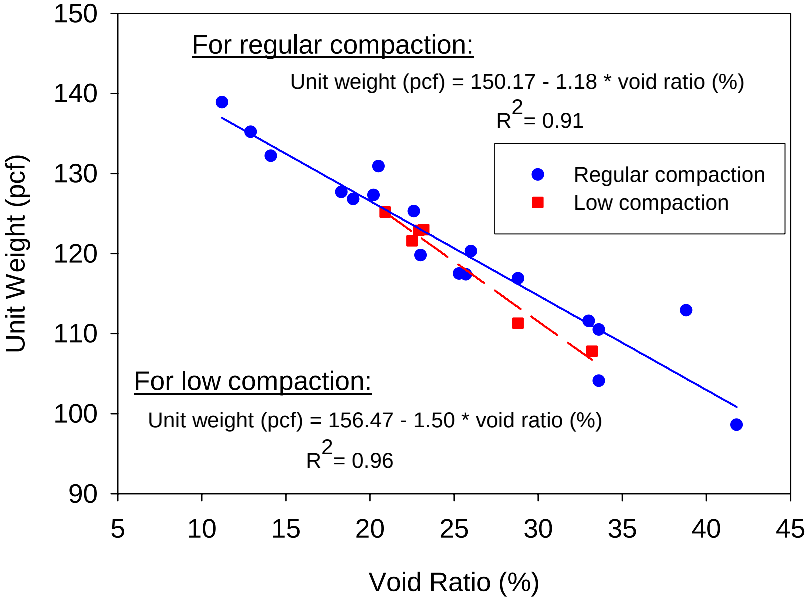


Figure 22. Effect of compaction energy on unit weight for all aggregates used

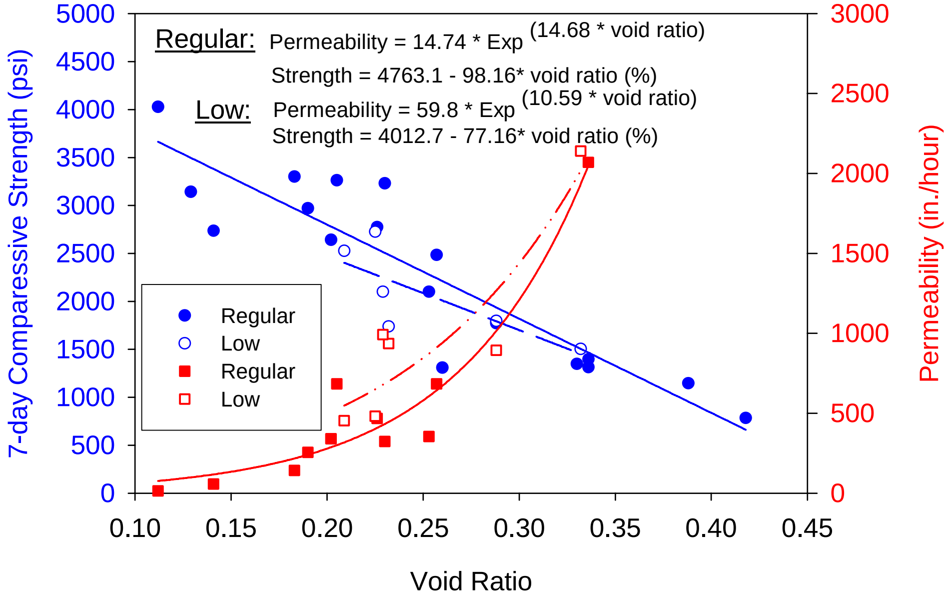


Figure 23. Effect of compaction energy on seven-day compressive strength and permeability trends for all aggregates used

Key Findings from Laboratory Testing

- For the three sizes of river gravel tested (No.4, 3/8-inch, 1/2-inch), larger aggregate produces concrete with a higher void ratio.
- Stronger river gravel aggregate produces PCPC with a higher strength than that of the crushed limestone.
- Using sand and/or latex in PCPC mixes increases strength and reduces permeability for both types of aggregate.
- Mixes containing only sand have a greater increase in strength than mixes containing sand and latex.
- Mixes containing silica fume have higher void ratios and lower strengths than baseline mixes with single-sized coarse aggregate, cement, and water.
- The compressive strength of samples containing both types of aggregates decreases linearly as the void ratio increases, with the strength of mixes that contain river gravel decreasing more rapidly than the strength of mixes containing limestone, as a function of void ratio.
- The unit weight of PCPC decreases linearly as the void ratio increases.
- Permeability increases exponentially as the void ratio increases, with a rapid increase in permeability when voids are above 25%.
- Mixes with a void ratio between 15% and 19% achieve both an adequate seven-day compressive strength of about 3,000 psi or more and a permeability between 135 and 240 inches/hour.
- It has been observed that mixes that achieve both the required strength and adequate permeability have a unit weight ranging from 127 pcf to 132 lbs/ft^3. This value of the

pervious concrete unit weight could be used as a quick quality control/quality assurance indicator at the time of placing pervious concrete.

- Compaction affects PCPC properties by reducing compressive strength, split strength, and unit weight and by increasing permeability.

FREEZE THAW RESULTS

Phase I

Of the Phase I mixes, two baseline mixes were selected for freeze-thaw testing, one containing river gravel (mix No. 4-RG) and one containing crushed limestone (mix 3/8-LS). The mass loss of these samples as a function of freeze-thaw cycles are shown in Figure 24. Mix No. 4-RG reached a 15% mass loss at 153 cycles, and mix 3/8-LS did so at 196 cycles, both primarily through aggregate deterioration.

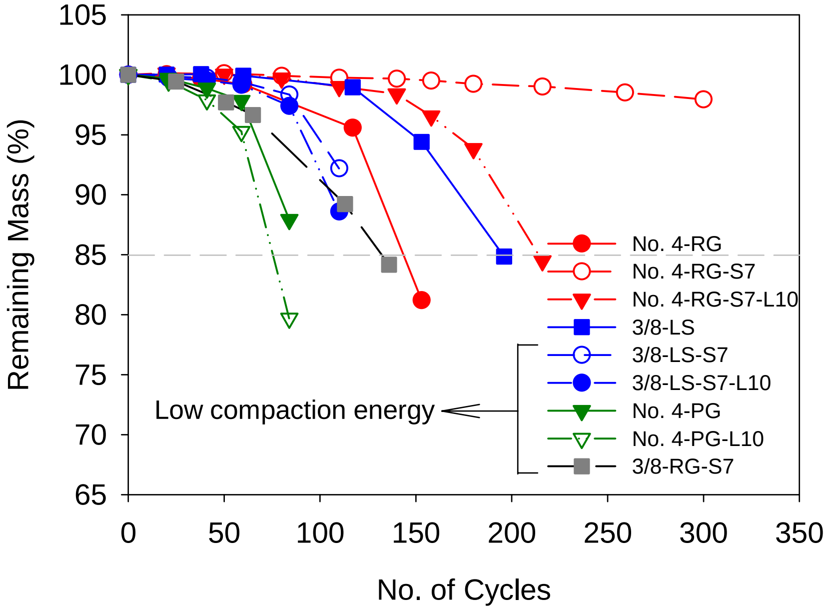


Figure 24. Results of freeze-thaw durability testing

Phase II

Phase II modified the mixes by adding only sand, only latex, and sand with latex. Figure 24 shows that samples of mix no. 4-RG-S7 did not fail after 300 cycles and experienced only 2.1% mass loss. However, other mixes failed before reaching 300 cycles. At failure, the mass losses of mixes No. 4-RG and No. 4-RG-S7-L10 were 18.8% and 15.5%, respectively. Figures 25 ad 26 present the freeze-thaw beams before and after testing for mixes No. 4-RG-S7-L10 and No. 4-RG-S7, respectively. These figures show a significant mass loss of sample No. 4-RG-S7-L10 compared with sample No. 4-RG-S7.

For low compaction energy, 3/8-RG-S7 failed at 136 cycles, with a mass loss of 15.8%. The pea gravel mixes (No. 4-PG and No. 4-PG-L10) failed at 84 cycles, with mass losses of 12.1% and 20.3%, respectively. Both mix mix 3/8-LS-S7-L10 and 3/8-LS-S7 failed at 110 cycles, as shown in Figures 27 and 28, respectively. At failure, the mass losses of samples 3/8-LS, 3/8-LS-S7, and 3/8-LS-S7-L10 were 15.2%, 7.8%, and 11.4%, respectively.


(a) Before freeze-thaw (b) After 216 freeze-thaw cycles

Figure 25. Failure of freeze-thaw beam for mix No. 4-RG-S7-L10 after 216 cycles


(a) Before freeze-thaw (b) After 300 freeze-thaw cycles

Figure 26. Freeze-thaw beam before and after testing for mix No. 4-RG-S7 after 300 cycles


(a) Before freeze-thaw (b) After 110 freeze-thaw cycles

Figure 27. Freeze-thaw beam showing failure of mix 3/8-LS-S7-L10 after 110 cycles


(a) Before freeze-thaw (b) After 110 freeze-thaw cycles

Figure 28. Freeze-thaw beam showing failure of 3/8-LS-S7 after 110 cycles

Effect of Aggregate Type and Size on Freeze-Thaw Durability

The mechanisms of PCPC failure when subjected to freeze-thaw cycles are either a result of aggregate deterioration or cement paste matrix failure. Aggregate failure is observed in the deterioration or splitting of the aggregate, in which a portion of an aggregate particle becomes separated from the concrete. Cement paste failure is observed in the unraveling of entire pieces of aggregate from the concrete. The mechanisms of failure for the tested mixes are summarized in Table 13. In general, mixes containing limestone (mix 3/8-LS) failed through the deterioration of the aggregate. However, mixes containing the smaller size No. 4 river gravel (mix No. 4-RG) failed due to aggregate deterioration and splitting. Mixes containing river gravel larger than No. 4 (3/8 inch) failed due to entire aggregate pieces becoming detached from the cement matrix. Although there are exceptions for each failure mode, these are the general trends observed during this study. Figures 25 and 26 show beams of mixes No. 4-RG-S7-L10 and No. 4-RG-S7 at the beginning and the end of freeze-thaw tests. The figures illustrate the significant mass loss in mix No. 4-RG-S7-L10. The majority of the mass loss was through splitting of the aggregates.

Table 13. Mechanisms of freeze-thaw failure

Mix	Compaction energy	Primary failure type
No. 4-RG	Regular	Aggregate
No. 4-RG-S7	Regular	No failure
No. 4-RG-S7-L10	Regular	Aggregate
3/8-LS	Regular	Aggregate
3/8-LS-S7	Low	Aggregate
3/8-LS-S7-L10	Low	Aggregate + paste
No. 4-PG	Low	Aggregate + paste
No. 4-PG-L10	Low	Aggregate + paste
3/8-RG-S7	Low	Paste

Effect of Sand and Latex on Freeze-Thaw Durability

The test results of mix No. 4-RG-S7-L10 show less freeze-thaw resistance than mix No. 4-RG-S7, in which sand and air entrainment were used. Although latex has some inherent air entraining ability (AEA), the samples containing a standard AEA showed better freeze-thaw resistance than the sample relying on latex for air entrainment. Pea gravel mixes placed using low compaction energy (mixes No. 4-PG and No. 4-PG-L10), which included AEA whether the mix contained latex or not, failed at 84 cycles. This indicates a weak freeze-thaw durability. These freeze-thaw test results also indicate that pervious concrete made with river gravel and 7% river sand (90% passing sieve No. 8) showed the best performance among all prepared mixes.

Effect of Compaction on Freeze-Thaw Durability

It was noted earlier in this report that two different compaction energies were used to prepare PCPC samples. Of the nine mixes on which freeze-thaw durability tests were performed, five of those mixes were prepared using low compaction energy. Three of the five low compaction energy samples failed by fracturing into three or four equally sized sections before reaching 15% mass loss (mixes 3/8-LS-S7, 3/8-LS-S7-L10, and No. 4-PG). This was not observed for any other samples. Furthermore, samples prepared at regular compaction energy failed through the aggregate, while failure through aggregate and paste was observed for mixes prepared at low compaction energy. The other two mixes (3/8-RG-S7 and No. 4-PG-L10) failed before completing 150 cycles. All mixes compacted using the higher energy completed 150 cycles, with the majority failing after 200 cycles. Therefore, it is concluded that compaction has an important effect on PCPC strength and freeze-thaw durability and needs further investigation.

Key Findings from Freeze-thaw Testing

- The mechanisms of PCPC failure when subjected to freeze-thaw cycles are a result of either aggregate deterioration or cement paste matrix failure. In general, mixes containing limestone (mix 3/8-LS) failed through deterioration of the aggregate. However, mixes containing the smaller size No. 4 river gravel (mix No. 4-RG) failed due to aggregate deterioration and splitting.
- Mixes that contained sand and/or latex had better freeze-thaw resistance than those that did not.
- Mixes containing single-sized river gravel with 7% sand showed the best performance when subjected to freeze-thaw cycles, with 2% mass loss after 300 cycles.
- Samples prepared at regular compaction energy failed through the aggregate, while failure through aggregate and paste was observed for mixes prepared at low compaction energy.
- Compaction energy has a significant effect on the freeze-thaw durability of PCPC. Therefore, further investigation of the effects of compaction on PCPC properties is recommended.

SUMMARY AND CONCLUSIONS

Low strengths and limited freeze-thaw test results have hindered the use of pervious concrete in the Midwestern and Northeastern United States. However, pervious concrete mixes that posses adequate strength, permeability, and freeze-thaw resistance were developed.

Relevant Literature

- The advantages of pervious concrete include improving skid resistance by removing water during rainy days, reducing noise, minimizing the heat island effect in large cities, preserving native ecosystems, and minimizing costs in some cases.
- A typical cross-section of pervious pavement consists of a pervious concrete layer (4 to 6 inches thick), a permeable base with a thickness up to 18 inches, and a permeable subgrade. If the subgrade permeability is low, drainage pipes could be used to drain water, which could increase the cost of the system.
- Typical mix design of pervious concrete used in the United States consists of cement, single-sized coarse aggregate (between the one-inch and No. 4 sieve sizes), and a water to cement ratio ranging from 0.27 to 0.43. The 28-day compressive strength of pervious concrete ranges from 800 psi to 3,000 psi, with a void ratio ranging from 14% to 31% and a permeability ranging from 36 inches/hour to 864 inches/hour.

Mixing Proportion and Mixing Procedures

- Two types of single-sized coarse aggregate, crushed limestone and river gravel, were used in this study. Three sizes of single-sized river gravel were used: (1) 1/2-inch size, with 100% passing the 5/8-inch and 100% retained on the 1/2-inch sieve; (2) 3/8-inch size, with 100% passing the 1/2-inch and 100% retained on the 3/8 inch sieve; and (3) No. 4 size, with 100% passing the 3/8-inch and 100% retained on the No. 4 sieve. Additionally single-sized 3/8-inch crushed limestone and two gradations of commercially available river gravel, known as pea gravel, were used. The effects of using a small percentage of sand, latex, and silica fume on pervious concrete engineering properties were investigated.
- The dry rodded unit weight, the void ratio, the specific gravity, and the abrasion resistance of river gravel and crushed limestone aggregates were determined. These properties indicate that river gravel has a higher unit weight and abrasion resistance than crushed limestone.
- Dry mixing of 1% of the cement with the aggregate was performed for one minute. Samples that employed this modified mixing procedure failed through the aggregate and increased the seven-day compressive strength of the mix.
- The cement content used in the prepared mixes was varied to reduce excess paste content. A binder to aggregate ratio of 0.21 and water to cement ratio of 0.27 was found to be optimum in terms of strength, permeability, and void ratio. Mixes were prepared using percentages of latex ranging from 0% to 15% by weight of solids to cementitious materials. In comparing seven-day strengths, it was found that the optimum latex content is 10%.

- All specimens were placed by rodding 25 times in three layers while applying a vibration for five seconds after rodding each layer. To evaluate the effect of compaction on pervious concrete properties, two vibrating amplitudes of 0.005 and 0.0034 inches, identified as regular and low compaction energies, respectively, were used.

Laboratory Test Results

- For the three sizes of river gravel (No.4, 3/8-inch, 1/2-inch), larger aggregate sizes produce concrete mixes with higher void ratios. Pervious concrete mixes made from aggregates with higher abrasion resistance results in higher strength PCPC.
- Adding sand and/or latex increases strength and reduces permeability for both aggregate types. Mixes containing only sand experience a greater increase in strength than mixes containing sand and latex. Mixes containing silica fume have higher void ratios and lower strengths than the mixes without.
- Pervious concrete engineering properties vary as a function of void ratio. The compressive strength decreases linearly as the void ratio increases, unit weight decreases linearly as the void ratio increases, and permeability increases exponentially as the void ratio increases, with a rapid increase in permeability at void ratios greater than 25%.
- Overall, results at regular compaction energy indicate that mixes with void ratios between 15% and 19% produce seven-day compressive strengths ranging from 3,300 to 2,900 psi and permeability factors ranging from 135 to 240 inches/hour. These mixes had unit weights between 127 and 132 pcf. Furthermore, the split strength of PCPC was found to be about 12% of the compressive strength.
- Freeze-thaw test results indicate that a mass loss of about 15% represents a terminal serviceability level for a pavement surface. Mixes that contain sand, latex, or both have better freeze-thaw resistance than baseline mixes containing only single-sized aggregate. Mixes that contain single-sized aggregate with sand have the best freeze-thaw resistance. Mix No. 4-RG-S7 with air entrainment showed the best freeze-thaw durability, with 2% mass loss after 300 cycles.
- Compaction affects PCPC properties by reducing compressive strength, split strength, and unit weight and by increasing permeability.
- Results presented in this report suggest that well-designed pervious concrete mixes can meet the strength, permeability, and freeze-thaw resistance requirements for cold weather climates.

FUTURE RESEARCH

Effect of Aggregate Properties

Although a limited number of aggregate sizes and types were evaluated in this study, it is concluded that aggregate engineering properties (abrasion resistance, which indicates strength) must be evaluated to design high-quality PCPC. Creating freeze-thaw-durable PCPC mixes that can function throughout the United States will require evaluating a larger variety of aggregates that represent the typical varieties found across the United States. Evaluating more aggregate types will allow the development of a minimum aggregate quality specification to produce durable PCPC.

Effect of Compaction

Preliminary results indicate that compaction energy affects PCPC properties, with the most pronounced effect on freeze-thaw behavior. More research is required to determine the relationship between compaction energy and PCPC properties that include strength, void ratio, permeability, and freeze-thaw durability. By determining this relationship, standardized methods for PCPC placement can be developed and modified to produce high-quality PCPC, and performance can be predicted through calibration with lab-scale methods.

Other Methods of Strength Improvement

This study evaluated the effects of using silica fume, latex, and sand to improve PCPC properties. Other materials exist that may increase PCPC strength and durability. Polypropylene fibers, for instance, add tensile strength and durability to standard concrete and should be evaluated in pervious concrete. Preliminary results show that fibers increase both compressive and split strength without affecting void ratio or permeability.

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APPENDIX

Void Continuity Index for Pervious Concretes Using X-Ray Computed Tomography Scanning

by

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INTRODUCTION

Portland cement pervious concrete (PCPC) is a specially designed concrete mixture with a void structure such that water can drain through the material. One characteristic of the unique mix design is that it is made without the fine aggregate portion, which normally fills voids between the larger aggregate particles. By using only the larger aggregate fraction and a relatively uniform aggregate size, an open and connected void structure can be created. A potential benefit of PCPC is the ability to drain and store stormwater locally beneath parking lots, driveways, etc. This prevents water runoff and potentially reduces water contamination.

To fully evaluate the matrix of voids that allow water to flow through the concrete, it is important to be able to view samples internally in three dimensions (3-D). That need is met nondestructively by using X-ray computed tomography (X-ray CT). This report describes the preliminary experimental results using X-ray CT on four PCPC lab samples produced from different mixtures of aggregates, cement, and water-cement ratios.

OBJECTIVES

The objectives of applying X-ray CT in the analysis of PCPC are the following:

1. Scan and digitally reconstruct high quality 3-D images of PCPC cylinders
2. View pore spaces/pathways and quantify their continuity

BACKGROUND

X-ray CT offers the world of material engineering the unique ability to view internal characteristics of specimens nondestructively. This ability is made possible by using measurements of X-ray attenuation, which is a function of material density. In short, the product of this type of analysis is volumetric maps of material densities. The process works by positioning a sample inside an X-ray fan beam and casting its shadow upon a special camera or detector that translates X-ray energy into electrical current (see Figure A.1). As the sample is rotated inside the X-ray fan beam, this shadow is translated into a two-dimensional cross-section. By measuring several of these cross-sections at small intervals, the cross-sections can be stacked one upon another to form 3-D digital representations of density.

At Iowa State University's Center for Nondestructive Evaluation, complete microfocus X-ray CT systems have been created, including the development of customized software for data acquisition, volumetric file reconstruction, and visualization. A 64-node Linux computer cluster is used in the CT reconstruction. The chamber used for these scans utilizes a 130-kilovolt microfocus X-ray tube capable of 2.5-micron resolution and 1400x1400x500-voxel (3-D resolution unit) data volumes (Zhang et al. 2003).

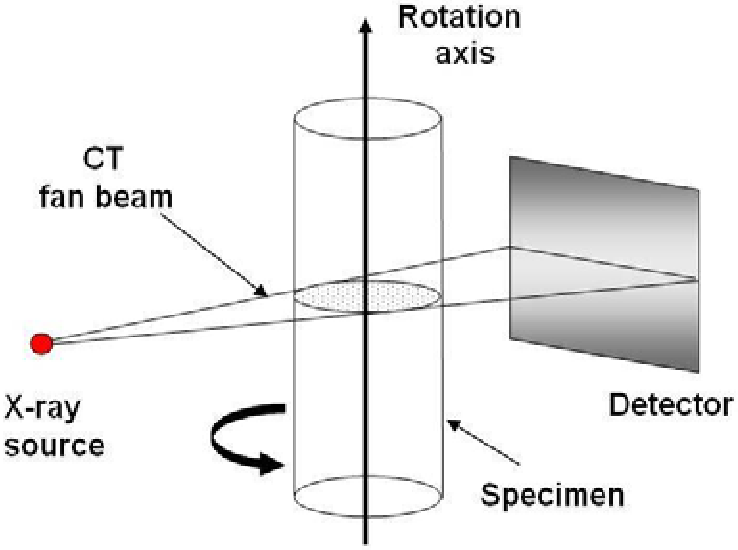

Figure A.1. CT scanning setup

MATERIALS

Four PCPC samples were prepared using the procedures outlined in this report, shown in Table A.1. Samples were saw cut into two equal-sized cylinders prior to X-ray CT scanning, resulting in three-inch by three-inch cylinders (see Figure A.2).

Table A.1. Four mix designs scanned

Mix no.	Aggregate type	Size	Cement (lbs/yard)	Water/ cement	Void ratio	k (in./hr)
3/8”-LS	Limestone	3/8”	550	0.27	0.34	2052
No. 4-RG-S7-L10	River gravel	#4	520	0.22	0.19	256
No. 4-RG-S7	River gravel	#4	571	0.27	0.18	155
No. 4-RG	River gravel	#4	578	0.27	0.25	353

METHODOLOGY

The PCPC samples illustrated in this report were scanned to produce volumetric files dimensioned at 640x640x310 voxels, resulting in a cross-sectional resolution of 0.20 mm and a vertical resolution of 0.33 mm. Scans were conducted at 130 kV and 0.11 mA. A 0.005-inch copper filter was placed over the aperture of the X-ray tube to attenuate low-energy X-rays. These low-energy X-rays are absorbed more readily in the exterior of a sample’s volume than X-rays with greater energy, causing erroneously high-density values towards sample edges. Scans visually depict well-defined borders between solid aggregate or concrete and air phases within samples. See Figures A.3 through A.7. For Figure A.7, each sample type is portrayed with both solid and void phases (.1), only the solid phase (.2), and only the void phase (.3). Note that void surfaces in contact with the cut surface appear lighter than those lying behind.

Figure A.2. PCPC samples provided for X-ray CT scanning

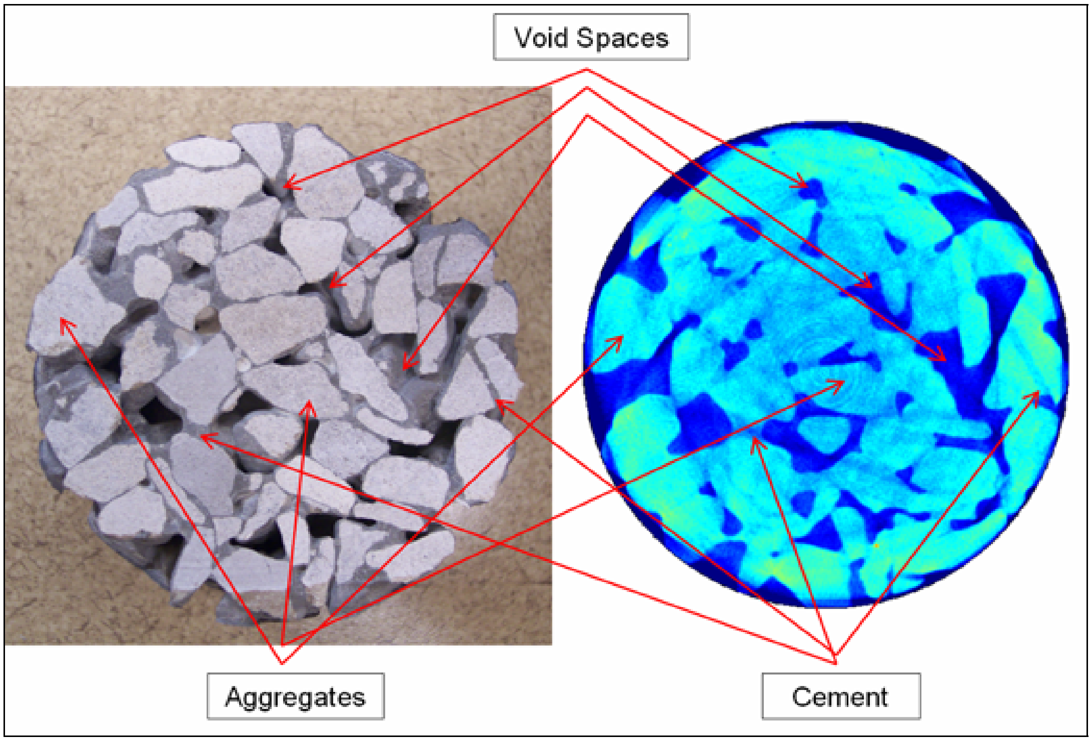

Figure A.3. Saw cut surface (left) and CT scan-produced surface (right) for the 3/8-inch-LS specimen

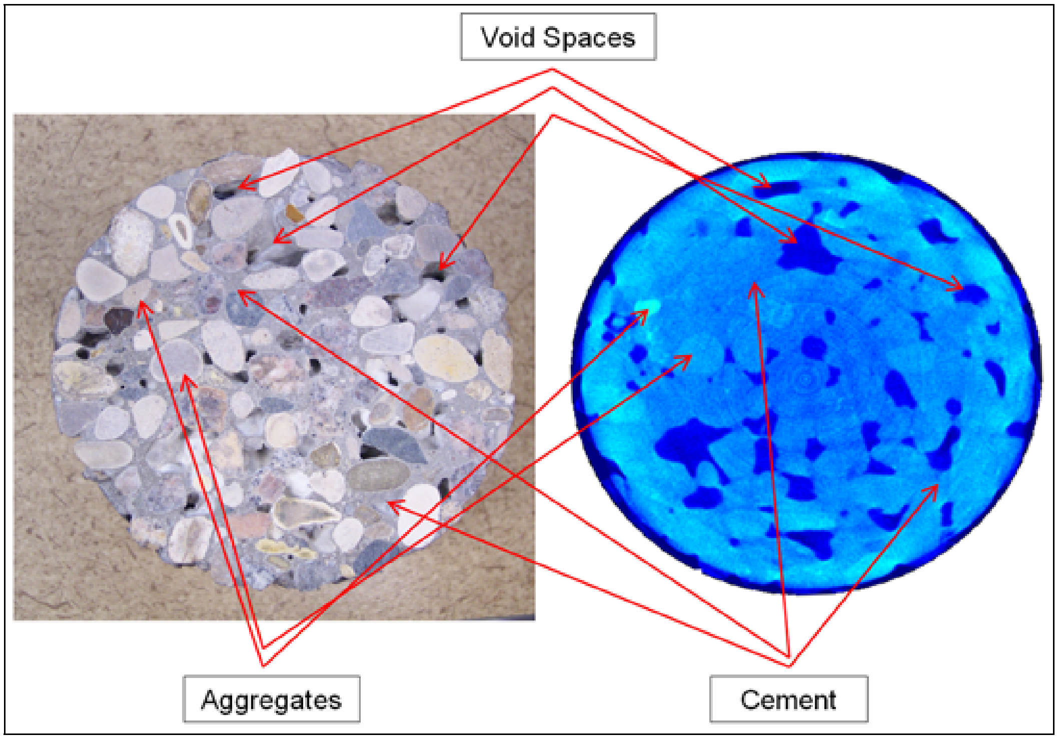

Figure A.4. Saw cut surface (left) and CT scan-produced surface (right) for the No. 4-RG-S7-L10 specimen

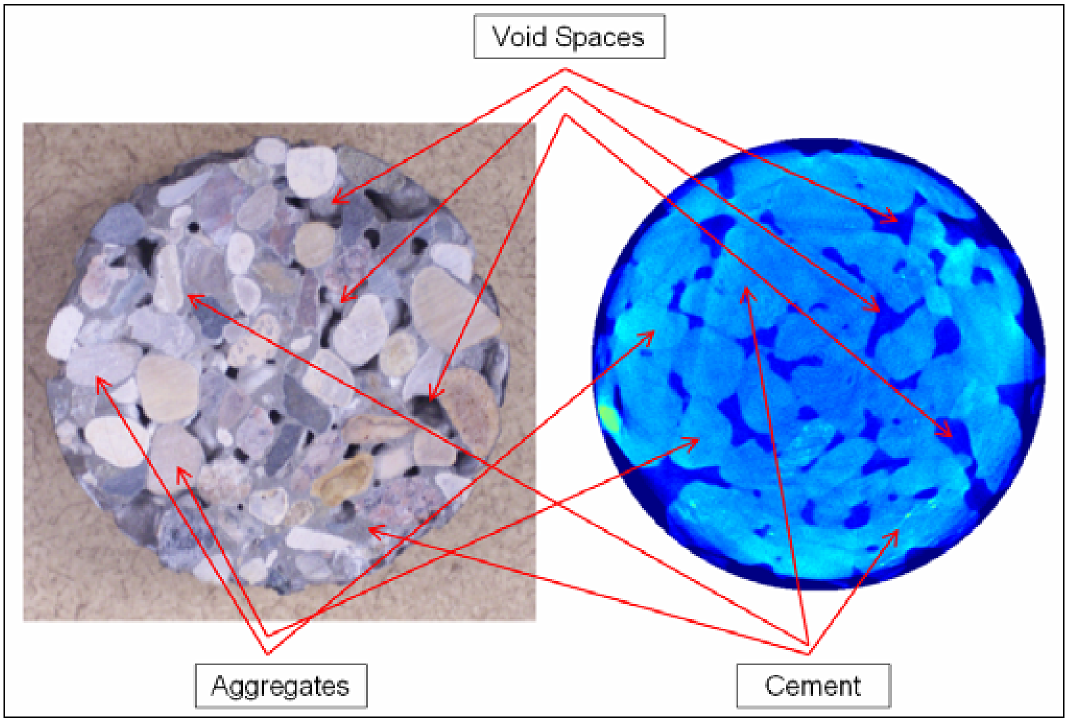

Figure A.5. Saw cut surface (left) and CT scan produced surface (right) for the No. 4-RG-S7 specimen

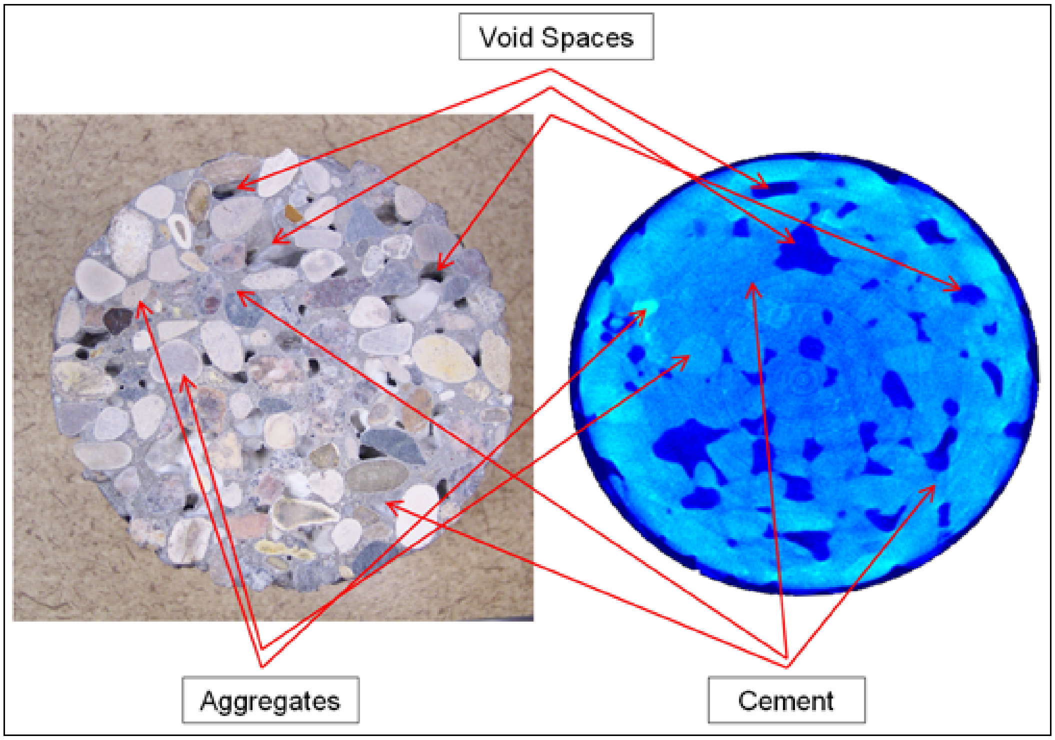

Figure A.6. Saw cut surface (left) and CT scan produced surface (right) for the No. 4-RG specimen

To quantify pore continuity in a sample, pore spaces were tracked vertically, starting from a centrally located horizontal cross-section. Tracking pore spaces was completed by viewing cross-sectional slices spatially in vertical order, one atop another, so that both vertical and lateral pore branching could be followed. Results are presented in terms of a void continuity index (VCI), an indication of whether or not pore spaces lead to radial (horizontal) or end (vertical) exits and also which direction from the central cross-section the successful continuity propagates towards (see Figure A.8). The equation for calculated VCI is expressed as the following:

$$VCI = \frac{\sum A_d}{\sum A_t} \qquad [1]$$

Where A_d is the total cross-sectional void area in the sample that has a drainage pathway out of the sample (radially or vertically) and A_t is the total cross-sectional void area at the mid-height of the sample across a horizontal slice.

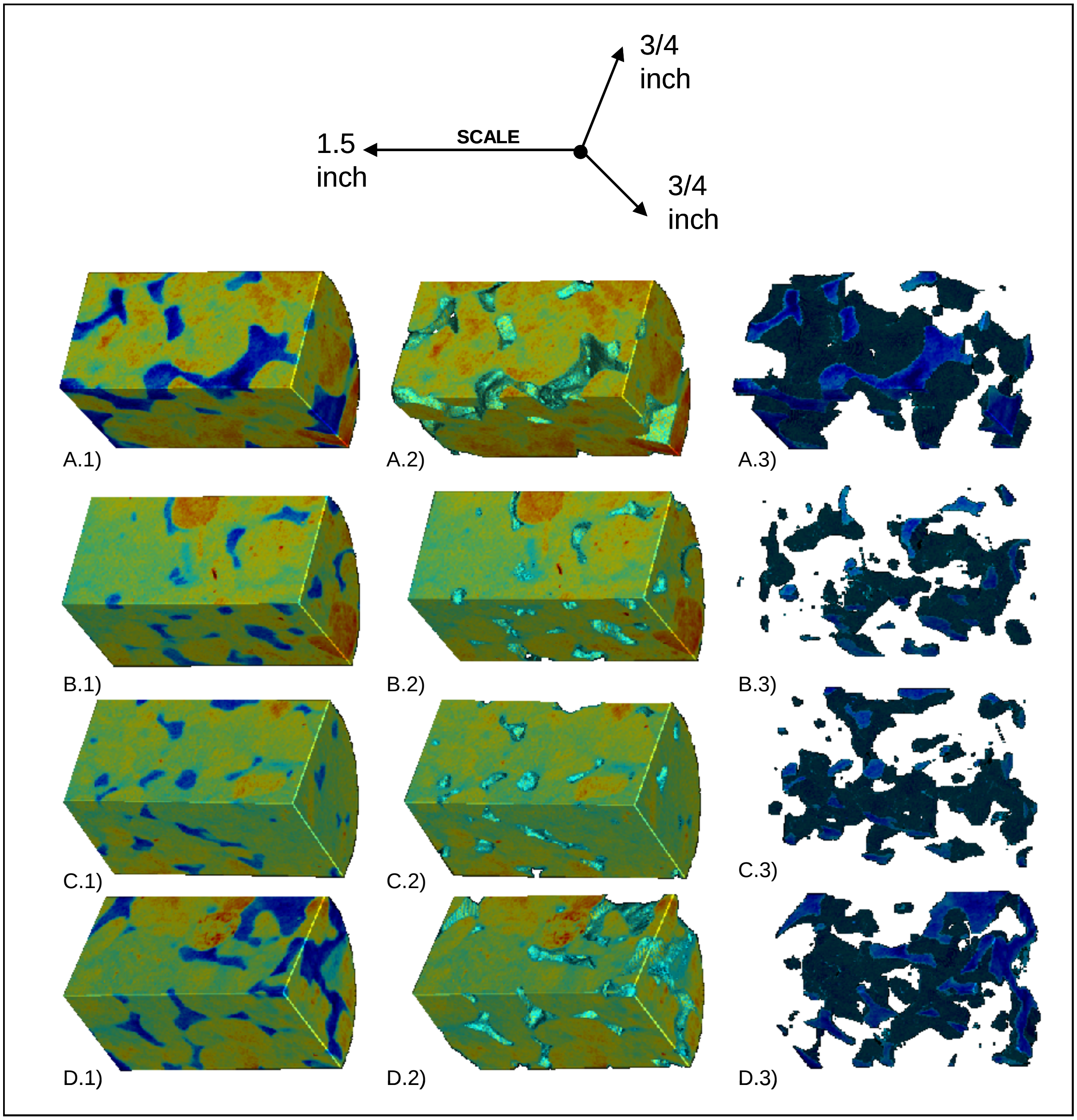

Figure A.7. Interior volumes from samples 3/8-inch-LS (A), No. 4-RG-S7-L10 (B), No. 4-RG-S7 (C), and No. 4-RG (D)

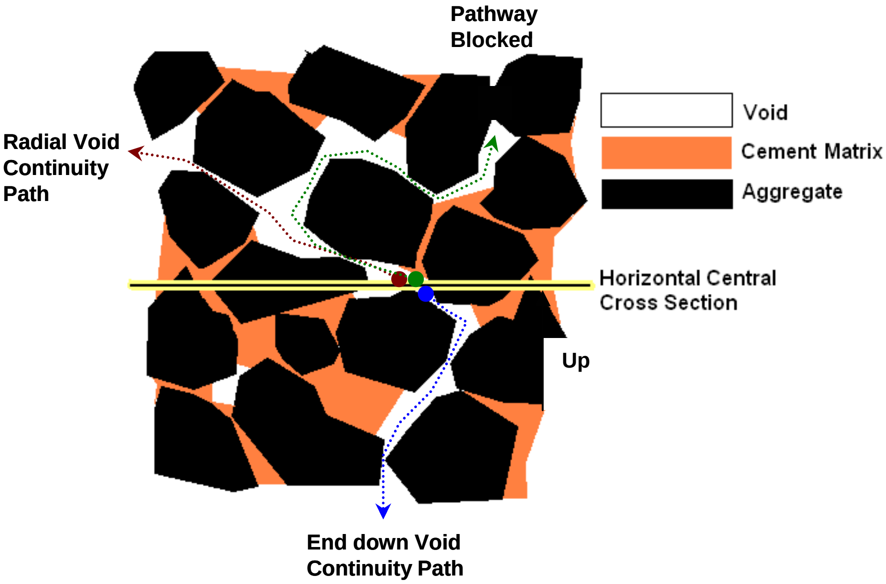

Figure A.8. Simulated interior vertical profile depicting only radial continuity traveling up and end continuity traveling down from the central cross-section

One central cross-section was analyzed per sample, and all voids dissected by cross-sectional slice are included in the analysis. These areas are sometimes split into multiple pore sections if the pore forks nearby. For instance, see voids OO and PP in the lower right-hand corner of sample No. 4-RG-S7 in Figure A.9). When mapping pores, the void path moved vertically; that is, the void could not backtrack to reach a radial or end exit. (For example, note that Figure A.8 does not exhibit end continuity traveling upwards.) This limiting of the void path was done to simplify the analysis, but it also has practical implications, as follows: (1) pore continuity may become clogged by sediments in field conditions, similarly to a trap in a sink; and (2) backtracking the water path would provide slower drainage through a void matrix when compared to a more direct route.

Once radial and end exit data were collected, the total areas attributed to successfully continuous voids along the central cross-section were computed digitally to compare with the total cross-sectional void area. This resulted in the percentage of successfully continuous pores.

RESULTS

Both end and radial continuity in upward and downward directions from a central cross-section are tabulated for all PCPC samples, as shown in Tables A.4–A.7. Each PCPC sample is also presented in a figure illustrating the sample's central cross-section and whether voids located within it are successful or unsuccessful for all continuity criteria (see Figures A.10–A.13). More concise results pertaining to the percentages of successfully continuous voids and averages thereof are tabulated in Table A.2). From these averaged results, a graph has been constructed of VCI versus laboratory-measured permeability. Best fit regression shows that a logarithmic relationship ($R^2 = 0.895$) exists between successful end continuity (average of up and down end continuity) and permeability (see Table A.3 and Figure A.14).

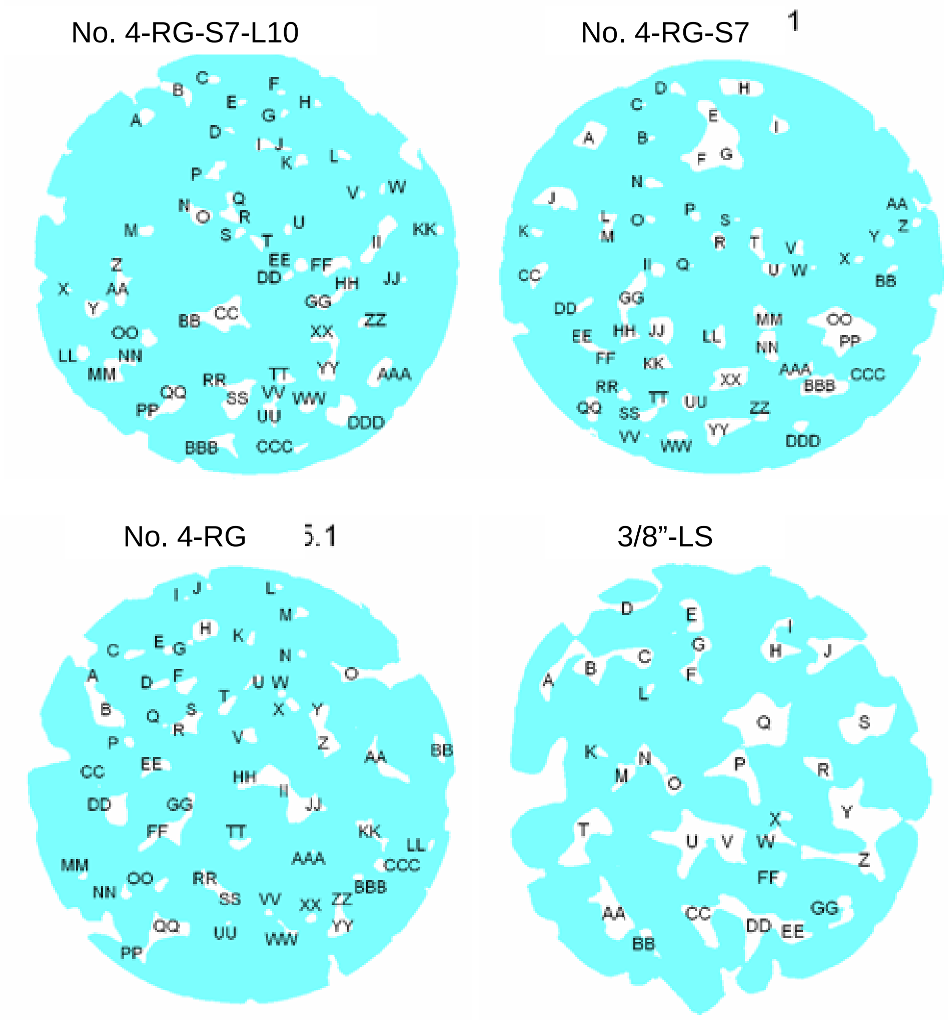

Figure A.9. Pore spaces on each PCPC sample central cross-section, numbered alphabetically

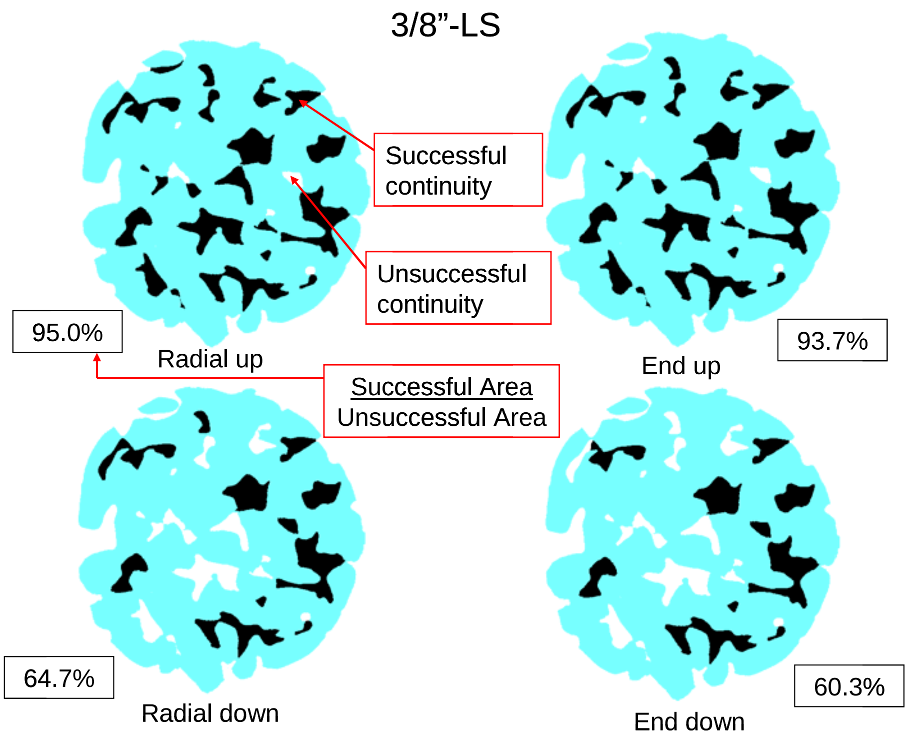

Figure A.10. Central cross-section pore continuity for sample 3/8-inch-LS

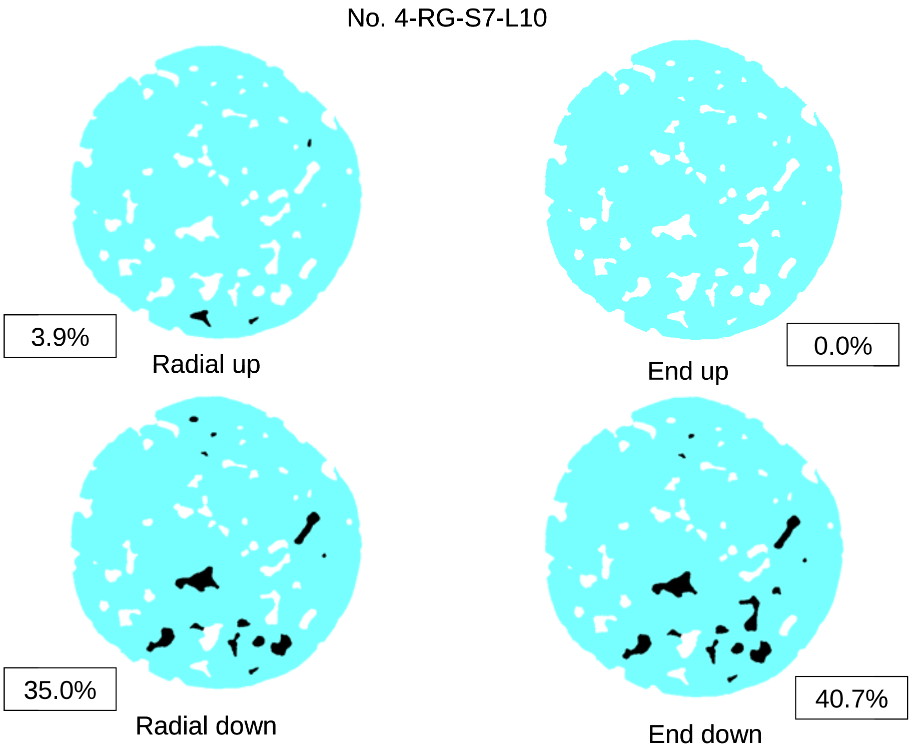

Figure A.11. Central cross-section void continuity for sample No. 4-RG-S7-L10

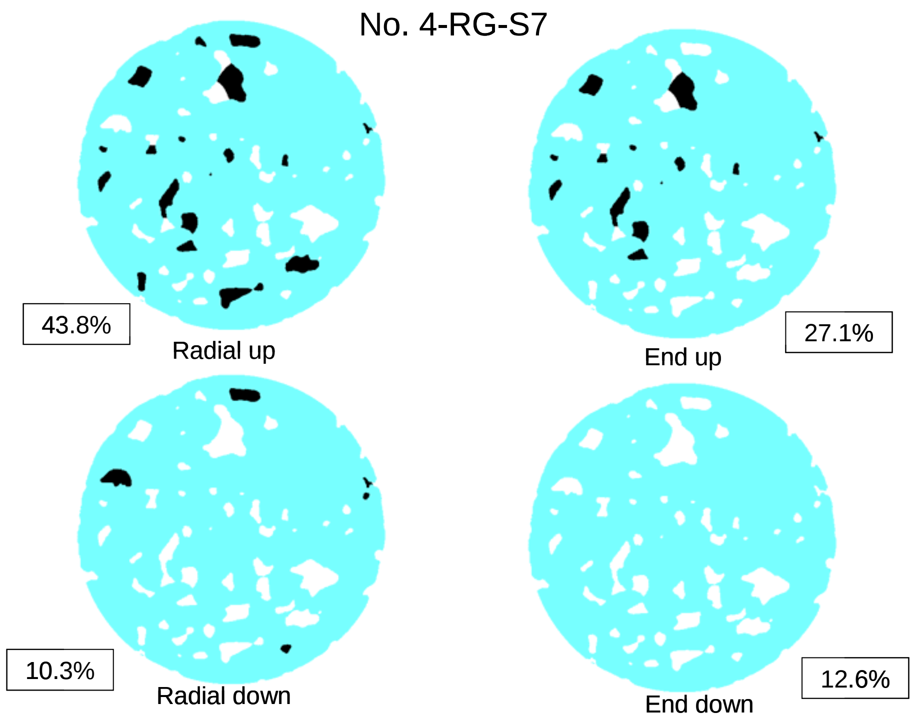

Figure A.12. Central cross-section void continuity for sample No. 4-RG-S7

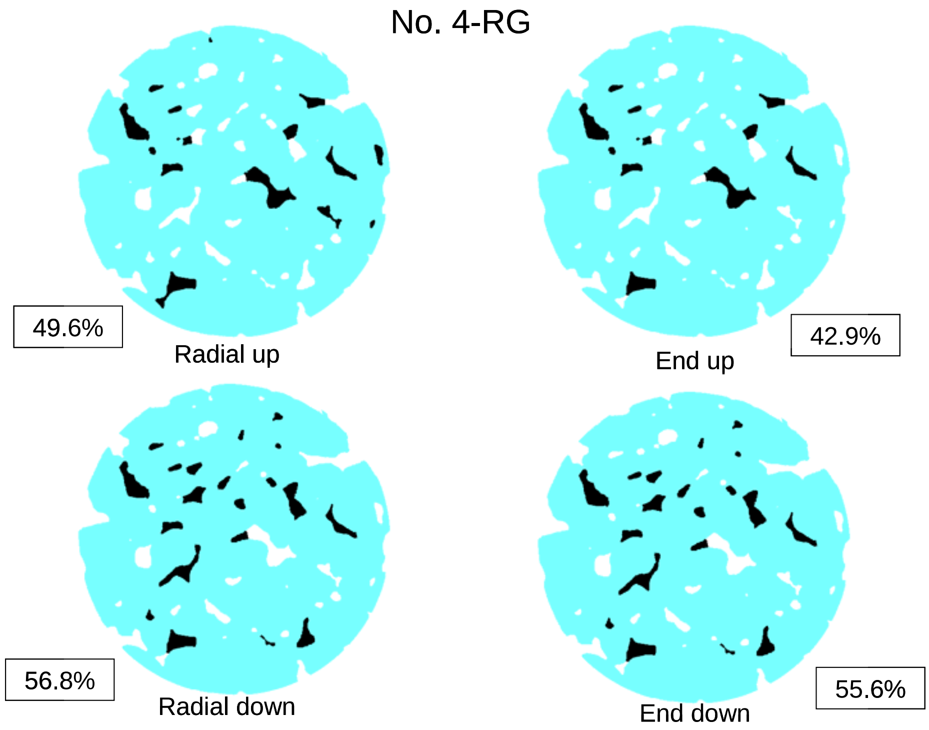

Figure A.13. Central cross-section void continuity for sample No. 4-RG

Table A.2. Percentages of successfully continuous voids and averages for all PCPC samples

	Directional continuity index (%)							
Mix No.	**End up**	**End down**	**End average**	**Radial up**	**Radial down**	**Radial average**	**Overall average**	**k (in./hr)**
3/8-inch-LS	93.7	60.3	77.0	95.0	64.7	79.9	78.4	2052
No. 4-RG-S7-L10	0.0	40.7	20.4	3.9	35.0	19.5	19.9	253
No. 4-RG-S7	27.1	12.6	19.9	43.8	10.3	27.1	23.5	155
No. 4-RG	42.9	55.6	49.3	49.6	56.8	53.2	51.2	353

Table A.3. R^2 regression model analysis of VCI averages

Continuity index average	R^2 values		
	Linear	**Power**	**Logarithmic**
End average	0.810	0.801	0.895
Radial average	0.776	0.691	0.834
Overall average	0.796	0.753	0.868

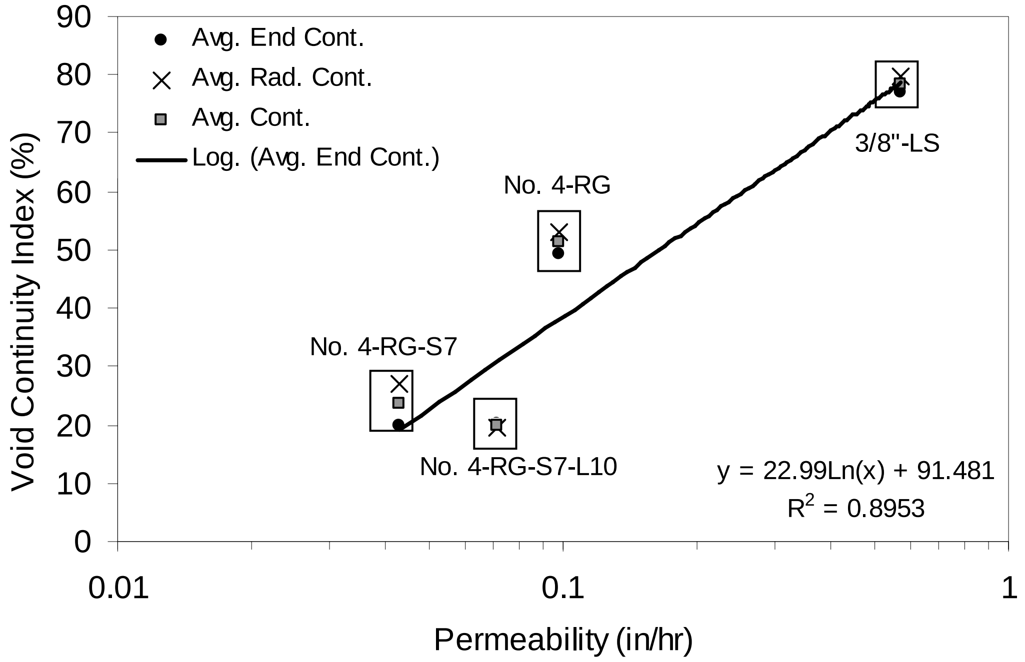

Figure A.14. Directional continuity percentage averages versus lab-determined permeability (best fit line is through averaged end continuity data)

Table A.4. Successful continuity tabulated for all pores along the central-cross-section of sample 3/8-inch-LS

Pore designation	Upward end continuity	Downward end continuity	Upward radial continuity	Downward radial continuity
A	YES	-	YES	YES
B	YES	YES	YES	YES
C	YES	YES	YES	YES
D	YES	-	-	-
E	YES	-	YES	YES
F	YES	-	YES	-
G	YES	-	YES	-
H	YES	-	YES	-
I	YES	-	YES	-
J	YES	YES	YES	YES
K	YES	-	YES	-
L	-	-	-	-
M	YES	-	YES	-
N	-	-	-	-
O	YES	-	YES	-
P	YES	-	YES	-
Q	YES	YES	YES	YES
R	-	YES	-	YES
S	YES	YES	YES	YES
T	YES	YES	YES	YES
U	YES	-	YES	-
V	YES	-	YES	-
W	YES	-	YES	-
X	-	-	-	-
Y	YES	YES	YES	YES
Z	YES	YES	YES	YES
AA	-	-	YES	-
BB	-	-	YES	-
CC	-	YES	YES	YES
DD	-	YES	YES	YES
EE	-	YES	YES	YES
FF	-	YES	YES	YES
GG	-	YES	YES	YES
HH	-	-	-	-

Table A.5. Successful continuity tabulated for all pores along the central cross-section of sample No. 4-RG-S7-L10

Pore designation	Upward end continuity	Downward end continuity	Upward radial continuity	Downward radial continuity
A	-	-	-	-
B	-	-	-	-
C	-	-	-	YES
D	-	YES	-	YES
E	-	YES	-	YES
-F	-	-	-	-
G	-	-	-	-
H	-	-	-	-
I	-	-	-	-
J	-	-	-	-
K	-	-	-	-
L	-	-	-	-
M	-	-	-	-
N	-	-	-	-
O	-	-	-	-
P	-	-	-	-
Q	-	-	-	-
R	-	-	-	-
S	-	-	-	-
T	-	-	-	-
U	-	-	-	-
V	-	-	-	YES
W	-	-	-	-
X	-	-	-	-
Y	-	-	-	-
Z	-	-	-	-
AA	-	YES	-	YES
BB	-	YES	-	YES
CC	-	-	-	-
DD	-	-	-	-
EE	-	-	-	-
FF	-	-	-	-
GG	-	-	-	-
HH	-	YES	-	YES
II	-	YES	-	YES
JJ	-	-	-	-
KK	-	-	-	-
LL	-	-	-	-
MM	-	-	-	-
NN	-	-	-	-
OO	-	YES	-	YES
PP	-	YES	-	YES
QQ	-	YES	-	YES
RR	-	-	-	-
SS	-	YES	-	YES
TT	-	YES	-	YES
UU	-	YES	-	YES
VV	-	YES	-	YES
WW	-	YES	-	-
XX	-	YES	-	-
YY	-	YES	-	-
ZZ	-	-	-	-
AAA	-	YES	YES	YES
BBB	-	YES	YES	YES
CCC	-	YES	-	YES
DDD	-	YES	-	YES

Table A.6. Successful continuity tabulated for all pores along the central cross-section of sample No. 4-RG-S7

Pore designation	Upward end continuity	Downward end continuity	Upward radial continuity	Downward radial continuity
A	YES	-	YES	-
B	-	-	-	-
C	-	-	-	-
D	-	-	YES	-
E	-	-	-	-
F	-	-	-	-
G	YES	-	YES	-
H	-	-	YES	YES
I	-	-	-	-
J	-	-	-	YES
K	YES	-	YES	-
L	-	-	-	-
M	YES	-	YES	-
N	-	-	-	-
O	YES	-	YES	-
P	-	-	-	-
Q	YES	-	YES	-
R	YES	-	YES	-
S	-	-	-	-
T	-	-	-	-
U	-	-	-	-
V	YES	-	YES	-
W	-	-	-	-
X	-	-	-	-
Y	-	-	-	-
Z	-	-	-	YES
AA	YES	-	YES	YES
BB	-	-	-	-
CC	YES	-	YES	-
DD	-	-	-	-
EE	-	-	-	-
FF	YES	-	YES	-
GG	-	-	-	-
HH	-	-	-	-
II	YES	-	YES	-
JJ	YES	-	YES	-
KK	-	-	-	-
LL	-	-	-	-
MM	-	-	-	-
NN	-	-	-	-
OO	-	-	-	-
PP	-	-	YES	-
QQ	-	-	-	-
RR	-	-	-	-
SS	-	-	-	-
TT	-	-	-	-
UU	-	-	-	-
VV	-	-	-	-
WW	-	-	-	-
XX	-	-	YES	-
YY	-	-	YES	-
ZZ	-	-	-	-
AAA	-	-	YES	-
BBB	-	-	-	-
CCC	-	-	-	YES

Table A.7. Successful continuity tabulated for all pores along the central cross-section of sample No. 4-RG

Pore designation	Upward end continuity	Downward end continuity	Upward radial continuity	Downward radial continuity
A	YES	YES	YES	YES
B	YES	YES	YES	YES
C	YES	-	YES	YES
D	YES	YES	YES	YES
E	-	-	-	-
F	-	YES	-	YES
G	-	-	-	-
H	-	-	-	-
I	-	-	-	-
J	-	-	YES	-
K	-	YES	-	YES
L	-	-	-	
M	-	YES	-	YES
N	-	YES	-	YES
O	YES	-	YES	-
P	YES	-	YES	-
Q	YES	-	YES	-
R	YES	YES	YES	YES
S	-	YES	-	YES
T	-	YES	-	YES
U	-	-	-	-
V	-	YES	-	YES
W	-	-	-	-
X	-	YES	-	YES
Y	YES	YES	YES	YES
Z	-	YES	-	YES
AA	YES	YES	YES	YES
BB	-	-	YES	-
CC	-	-	-	-
DD	-	-	-	-
EE	YES	YES	YES	YES
FF	-	YES	-	YES
GG	-	YES	-	YES
HH	-	YES	-	YES
II	YES	-	YES	-
JJ	YES	-	YES	-
KK	-	-	YES	-
LL	-	-	YES	-
MM	-	-	-	-
NN	-	YES	-	YES
OO	-	-	-	
PP	-	-	YES	
QQ	YES	YES	YES	YES
RR	-	-	-	-
SS	-	-	-	-
TT	-	-	-	-
UU	-	-	-	-
VV	-	-	-	-
WW	-	YES	-	YES
XX	-	-	-	-
YY	-	YES	-	YES
ZZ	-	YES	-	YES
AAA	-	-	-	-
BBB	-	-	-	-

DISCUSSION

The continuities from the X-ray CT-scanned samples can be ranked using comparative analysis against the results from Table A.2 and Figure A.14. Sample 3/8-inch-LS has the highest VCI values, followed by sample No. 4-RG, both with consistently higher results than those of samples No. 4-RG-S7 and No. 4-RG-S7-L10. Samples No. 4-RG-S7 and No. 4-RG-S7-L10 have similar averaged end continuity results.

Sample No. 4-RG-S7-L10 shows a high degree of variance between pore continuity propagating up versus down (0.0% compared to 40.7% of total pores, respectively). However, by viewing cross-sections within the sample it was determined that this variance is due to a large difference in void ratio within the sample (see Figure A.15). Cross-sections from the sample's top half show fewer voids than those from the sample's bottom. This variance shows that the void matrix structure in PCPC may be affected by concrete placement procedures.

When VCI results are compared to permeability results from the falling head permeameter, there is a relatively good (R^2=0.895) logarithmic relationship (see Figure A.14). However, there is a large discrepancy in permeability between the two least permeable samples (samples No. 4-RG-S7 and No. 4-RG-S7-L10), though their average end continuity results are similar. This may be due to the ability of samples to allow water to flow along the sides, where the casting mold may have left a relatively open structure. For example, see Figure A.16, in which portions of concrete that seem flat would be firmly against the permeameter's latex sides. All other areas would freely transport water during permeability testing. Sealing gum, most of which has been removed, can be seen at the sample top. Although a ring of sealing gum was applied to the sides of cylinders near the sample ends, this may not have completely prevented water from trickling through most of the sample length at the sides and then re-entering the sample radially towards the sample base, above the sealing gum. This edge effect would not be accounted for by the continuity analysis, which focuses only on internal pores.

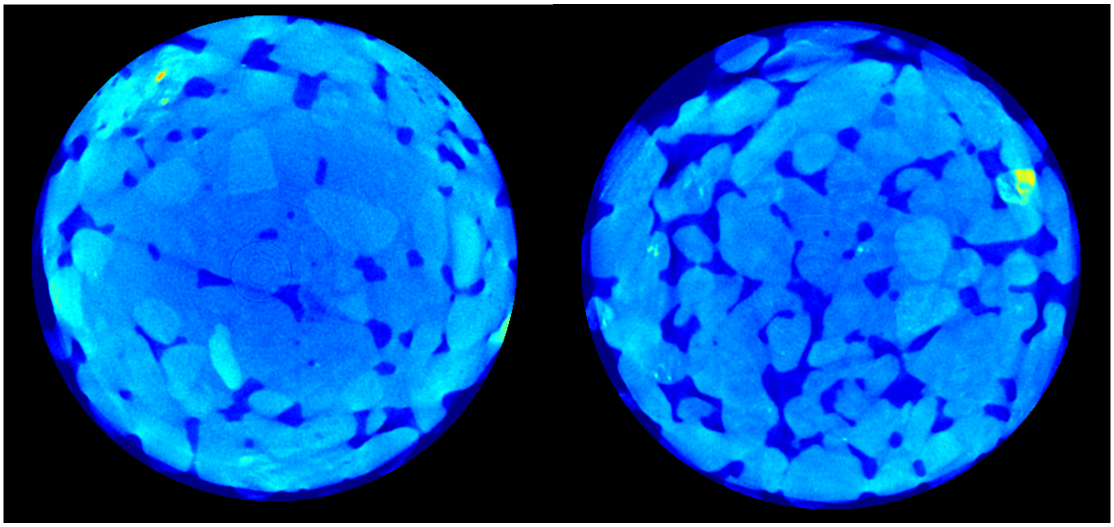

Figure A.15. Typical CT cross-sections from sample No. 4-RG-S7-L10, taken from the top (left) and bottom (right)

Figure A.16. Side view of PCPC, with high void continuity along sample sides

CONCLUSIONS

X-ray CT can be a useful tool for analyzing pervious concrete mixtures due to its ability to reveal internal structure and provide quantitative results. It was found that the results of pore continuity analysis compare well with falling head permeability test results, showing a logarithmic relationship with an R-squared value of nearly 0.90.

The ability to view internal slices of materials uncovered a high degree of void heterogeneity within various samples. The samples used in this X-ray CT scanning were initial mixes in which nonhomogeneity occurred. In subsequent mixing trials, greater attention was paid to sample preparation to minimize such nonhomogeneity. The X-ray CT scanning process outlines herein should be continued on new samples to investigate the relative homogeneity of later mixes.

RECOMMENDATIONS

The continuity analysis of PCPC permeability based on X-ray CT scanning should prove even more beneficial as a database of scanned cylinders grows. Relations between measured VCI and sample permeability will become better understood with further testing. It is advised that X-ray CT be used throughout the mix design processes of new pervious concretes so the effectiveness of sample porosity can be evaluated. Furthermore, it is recommended that X-ray CT scans be performed on field cores to evaluate homogeneity and the implications of clogging.

WORKS CITED

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