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Pervious Concrete Physical Characteristics and Effectiveness in Stormwater Pollution Reduction

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Final Report
April 2016

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Institute for Transportation

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16. Abstract

The objective of this research was to investigate the physical/chemical and water flow characteristics of various previous concrete mixes made of different concrete materials and their effectiveness in attenuating water pollution. Four pervious concrete mixes were prepared with Portland cement and with 15% cementitious materials (slag, limestone powder, and fly ash) as a Portland cement replacement.

All four pervious concrete mixtures had acceptable workability. The unit weight of the fresh pervious concrete mixtures ranged from 115.9 lb/yd^3 to 119.6 lb/yd^3, while the 28 day compressive strength of the pervious concrete mixes ranged from 1858 psi (mix with 15% slag) to 2285 psi (pure cement mix). The compressive strength generally increased with unit weight and decreased with total porosity (air void ratio). The permeability of the four mixes generally decreased with unit weight and increased with total porosity. The permeability coefficients ranged from 340 in./hr for the pure cement mix to 642 in./hr for the mix with 15% slag. The total porosities of the four pervious concrete mixes ranged from 24.00% (mix with 15% slag) to 31.41% (pure cement mix) as measured by the flatbed scanner test method, while the porosities ranged from 18.93% (mix with 15% slag) to 24.15% (pure cement mix) as measured by the RapidAir method. The total porosities of the four pervious concrete mixes measured by the flatbed scanner method were higher than those measured by the Rapid Air method, but the specific surface areas measured by the flatbed scanner method were all lower than those measured by the Rapid Air method. For the pollution abatement experiments, mixes with fly ash and limestone powder removed about 30% of the input naphthalene concentration, while the mix with slag only removed 0.5% of the influent naphthalene concentration. The water volume balance showed that less than 1% of the water added was retained in the experimental column setup.

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PERVIOUS CONCRETE PHYSICAL CHARACTERISTICS AND EFFECTIVENESS IN STORMWATER POLLUTION REDUCTION

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April 2016

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EXECUTIVE SUMMARY

The objective of the research was to investigate the physical/chemical and water flow characteristics of various pervious concrete mixes made of different concrete materials and their effectiveness in attenuating water pollution. Four pervious concrete mixes were prepared with Portland cement and with 15% cementitious materials (slag, limestone powder, and fly ash) as a Portland cement replacement.

All four pervious concrete mixtures had acceptable workability, with mixtures made with Portland cement and 15% fly ash replacement having better workability than those made with 15% slag and 15% limestone powder replacement. The unit weight of these fresh pervious concrete mixtures ranged from 115.9 lb/yd^3 to 119.6 lb/yd^3, with the mixture made with 15% slag having the lowest unit weight (115.9 lb/yd^3) and the mixture made with 15% fly ash having the highest unit weight (119.6 lb/yd^3). The 28 day compressive strength of the pervious concrete mixes ranged from 1858 psi (mix with 15% slag) to 2285 psi (pure cement mix). The compressive strength generally increased with unit weight and decreased with total porosity (air void ratio). The permeability of the four mixes generally decreased with unit weight and increased with total porosity. The permeability coefficients ranged from 340 in./hr for the pure cement mix to 642 in./hr for the mix with 15% slag. The total porosities (or air void ratios) of these pervious concrete mixes ranged from 24.00% (mix with 15% slag) to 31.41% (pure cement mix) as measured by the flatbed scanner test method, while the porosities ranged from 18.93% (mix with 15% slag) to 24.15% (pure cement mix) as measured by the RapidAir method. It was not clear why the concrete porosities were not correlated to unit weight. The total porosity of the four pervious concrete mixes measured by the flatbed scanner method were all higher than those measured by the Rapid Air method, but the specific surface areas measured by the flatbed scanner method were all lower than those measured by the Rapid Air method.

For the pollution abatement experiments, mixes with fly ash and limestone powder removed about 30% of the input naphthalene concentration, while the mix with pure cement removed 10% and the mix with slag only removed 0.5% of the influent naphthalene concentration. The water volume balance showed that less than 1% of the water added was retained in the experimental column setup.

1 INTRODUCTION

1.1 Research Background

Pervious concrete is an environmentally friendly and sustainable infrastructure with benefits such as stormwater reduction, stream/river peak flow rate reduction, groundwater recharge, pollutant abatement, heat island mitigation, noise reduction, and skid reduction (US EPA 2014). Typical applications of pervious concrete pavements include vehicle parking areas, sidewalks, pathways, driveways, and alleys. Pervious concrete allows rainfall to be drained and to percolate through the concrete to the subbase/subgrade materials, thereby reducing stormwater runoff and, at the same time, recharging the groundwater. Depending on the design of the pervious concrete system, a pervious concrete pavement and its subbase material may have sufficient water storage capacity such that a stormwater detention pond or swale may not be needed. In addition, pervious concrete pavement has the advantage of pollutant abatement in that it filters and retains stormwater runoff pollutants within the pervious concrete and the subbase materials.

Despite its many benefits, several aspects of pervious concrete have not been fully investigated. Some of these include pollutant attenuation for different pervious concrete mixes, the impact of the concrete pore structure (e.g., the pore surface area and flow path characteristics) on pollutant removal, the mechanism of pollutant abatement, and the potential for pervious concrete to experience subsurface contamination. Research has been conducted on plastic grids and small concrete block pavements (Bean et al. 2007), porous asphalt pavements (Legret and Colandini 1999), and commercially available permeable interlocking concrete pavements and plastic reinforcing grid pavers with gravel (Brattebo and Booth 2003).

1.2 Research Objectives

This research investigated the physical/chemical and water flow characteristics of various pervious concrete mixes made of different concrete materials and their effectiveness in attenuating water pollution. The pervious concrete mixes studied were made by replacing cement with different cementitious materials (slag, limestone, and fly ash) and were characterized for such physical properties as compressive strength, air void structure, and water permeability. Limited laboratory-scale column experiments were conducted to assess the pollutant attenuation properties of the pervious concrete mixes.

2 LITERATURE REVIEW

2.1 Introduction

Pervious concrete as described by the American Concrete Institute (ACI) is a "near-zero slump, open-graded material consisting of Portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water with void contents ranging from 15% to 35% and compressive strengths of 400 to 4000 psi (2.8 to 28 MPa)" (ACI 2006). The primary benefit offered by pervious concrete is its ability to transport water through its structure, thus reducing stormwater runoff and recharging groundwater. At the same time, pollutants may be attenuated as the stormwater flows through the pervious concrete and the subbase materials. In order to obtain the targeted void content and compressive strength, the proportions of the different cementitious materials and aggregate, the water-to-cement (w/c) ratio, and the casting and compaction procedure are important determining factors.

2.2 Pervious Concrete Mix

Material design for pervious concrete differs from that of conventional concrete in that a certain void content needs to be obtained in the material structure to provide adequate water flow performance and, at the same time, the necessary compressive strength. A description of pervious concrete mix design can be found in the ACI 522R report (ACI 2010). Because the void content (i.e., porosity) is one of the prominent characteristics of pervious concrete, the mix of cementitious materials, the aggregate used, the water-to-binder (w/b) ratio, and the binder-to-aggregate (b/a) ratio affect the final porosity of the prepared pervious concrete.

Aggregates

The recommended aggregate size number for pervious concrete ranges from #67 (3/4 in. to No. 4) to #89 (3/8 in. to No. 50). With regards to aggregate type, dolomite is believed to be the best aggregate to make porous concrete (Lian and Zhuge 2010). To obtain a specified porosity, fine aggregates are avoided or kept to a very small amount. For example, a study by Schaefer et al. (2006) showed that when 7% of the coarse aggregate was replaced by fine aggregate for a pervious concrete mixture, the permeability coefficient of the mixture decreased but the freeze-thaw durability, compressive strength, and flexural strength improved. Logically, increasing the pore sizes through the use of larger sized aggregate is a means to increase the permeability of the pervious concrete. Table 1 provides the typical range of mixture proportions and the water-to-cement ratios used.

Table 1. Typical mixtures of pervious Portland cement concrete

Materials	Mixture proportions/ratios
Cementitious materials (lb/yd^3)	450-700
Coarse aggregate (lb/yd^3)	2000-2500
Fine to coarse aggregate ratio by weight	0 - 1:1
Water-to-cement ratio by weight	0.27 - 0.4
Aggregate-to-binder ratio by weight	4 to 4.5:1
Air entraining agent (oz/cwt*)	2
Water reducer (oz/cwt)	6
Hydration stabilizer (oz/cwt)	6 - 12

* cwt = hundredweight = 112 lbs
Source: Tennis et al. 2004

Cementitious Materials or Binder

Most pervious mixes have between 450 and 700 pounds of cementitious materials, or binder, per cubic yard or 18% to 24% by weight of the concrete (Table 1). Portland cement and blended cement conforming to ASTM C595 (2015) "Standard Specification for Blended Hydraulic Cements" and ASTM C1157 (2011) "Standard Performance Specification for Hydraulic Cement" are used in pervious concrete (Tennis et al. 2004). In addition, other cementitious materials such as fly ash, slag, and silica fume conforming to ASTM C618 (2015) "Standard Specification for Coal Fly Ash and Raw or Calcined Nature Pozzolan for Use in Concrete," ASTM C 989 (2014) "Standard Specification for Slag Cement for Use in Concrete and Mortars," and ASTM C1240 (2015) "Standard Specification for Silica Fume Used in Cementitious Mixtures," respectively, have been used in the preparation of pervious concrete.

Water-to-binder (w/b) Ratio

A w/b ratio between 0.27 and 0.30 is preferred for pervious concrete. A w/b ratio less than 0.27 can result in very low workability for pervious concrete. On the other hand, a high w/b ratio may lead to a mixture with excessive paste segregated at the bottom of the mold or formwork and can cause lower permeability than anticipated after hardening (Kevern et al. 2009). Table 2 shows the effects of w/b ratio on the properties of pervious concrete.

Binder-to-aggregate (b/a) Ratio

The b/a ratio primarily depends on the final application of the pervious concrete and the mixture materials used. A low or high b/a ratio determines how thin or thick a paste layer will coat the aggregate particles and how much paste may fill the void spaces. The typical b/a ratio used is between 0.22 and 0.25. Table 2 shows the effects of b/a ratio on the properties of pervious concrete.

Table 2. Effects of water-to-cement and binder-to-aggregate ratios on pervious concrete properties

<table>
<tr><th>Ratio</th><th>Proper Range</th><th>Too Low</th><th>Too High</th></tr>
<tr><td>Water-to-cement</td><td>0.27 - 0.30 (by weight)</td><td>Reduced concrete workability</td><td rowspan="2">Results in a layer of paste segregated at the bottom of concrete, reduced hydraulic conductivity</td></tr>
<tr><td>Binder-to-aggregate</td><td>0.18 - 0.22 (by volume)</td><td>Reduced concrete strength and freeze-thaw durability</td></tr>
</table>

Source: Tong 2011

Additives

Additives such as retarder or hydration controlling admixture, water-reducing admixture, or viscosity modifying admixture and air-entraining admixture may be added.

2.3 Consolidation of Pervious Concrete

The degree of compaction and the compaction procedures/methods are two of the most important factors influencing the mechanical properties of pervious concrete. It has been found that increasing the fresh concrete unit weight, increasing the amount of fine aggregates in the mixture, and applying a high compaction effort can improve such mechanical properties as compressive strength but decrease the hydraulic performance (permeability) and void ratio (Bean et al. 2007, Schaefer et al. 2006). To get the best surface finish, required strength, and permeability, proper compaction is important. Too little compaction may not provide the required strength or a smooth surface, and it may also cause potential raveling of the finished pavement. Too much compaction may cause a decrease in permeability by closing the voids. For a given mixture, the permeability can vary by as much as 25% for different compaction levels. As such, it is important to control the compaction energy accurately and quantitatively to obtain batches of pervious concrete with similar properties. In addition, a maximum thickness of 6 in. of pervious concrete is recommended because studies have shown that the concrete at the bottom quarter of a pervious concrete pavement often has a lower strength and/or lower porosity than the concrete at the top layer of the pavement (MCIA 2002).

2.4 Physical Characterization

The physical properties typically used to characterize pervious concrete are unit weight, compressive strength, permeability, air voids, and porosity.

Unit Weight

Unit weight, which describes the density of fresh pervious concrete, is a good indicator of its mechanical and hydrological properties and offers the best routine test for monitoring the quality of pervious concrete. The unit weight of concrete is determined based on ASTM C1688 (2008).

Depending on the mixture, the materials used, and the compaction levels and procedures, the unit weight of fresh pervious concrete is commonly between 105 lb/ft^3 and 120 lb/ft^3 (1680 to 1920 kg/m^3). The porosity of pervious concrete can be determined from the unit weight, and therefore the compressive strength can be predicted based on the relationship between void ratio and compressive strength (Kevern et al. 2008, Tennis et al. 2004).

Compressive Strength

Compressive strength is used in the structural design of pervious concrete pavement and is determined based on ASTM C39 (2003). Pervious concrete mixtures can have compressive strengths ranging from 500 psi to 4000 psi (3.5 MPa to 28 MPa). The typical pervious concrete compressive strength is approximately 2500 psi (17 MPa) (Tan et al. 2003). Zouaghi et al. (2000) showed that the compressive strength of a mix is linearly proportional to unit weight but inversely proportional to void ratio.

Permeability

The permeability of pervious concrete is a measure of the water flow through the pore spaces or fractures in the pervious concrete. The permeability of pervious concrete is determined using the falling head permeability test and is estimated based on Darcy's Law. Permeability is an important parameter used in the hydrological design of pervious concrete. Typical permeability values range from 3 gal/ft^2/min (120 L/m^2/min or 0.2 cm/s) to 17 gal/ft^2/min (700 L/m^2/min or 1.2 cm/s) (Montes and Haselbach 2006).

Air Voids

The average pore sizes of pervious concrete typically range from 2 mm to 8 mm. The void ratio ranges from 15% to 35% by volume. The air void content of pervious concrete can be determined using either an automatic image analysis device, RapidAir, according to ASTM C457 (2012) "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete" or the flatbed scanner method (Peterson et al. 2009). Another method is the standard linear-traverse test method (ASTM C1754 2012). In contrast to ASTM C457, in ASTM C1754 the measured points are counted manually.

The RapidAir and the flatbed scanner methods are much less tedious than the manual test method. In the RapidAir method, a cross-section of a polished sample is stained with a black ink, and the voids are filled with a white material such as zinc paste, which allows the rapid air system to distinguish between the air voids and the concrete matrix. The RapidAir device automatically scans the sample surface and provides the air void parameters. Recent studies have shown that the RapidAir method has a high degree of multi-laboratory reproducibility and has less variation than the manual technique (Jakobsen et al. 2006). The RapidAir test method can determine the air content, specific surface area, and spacing factor. Research has shown a strong relationship between porosity/air content and spacing factor for conventional concrete using the RapidAir and flatbed scanner methods (Carlson et al. 2006). However, the air content measured by the RapidAir method was found to be slightly higher and the spacing factor was found to be slightly lower than those values measured by the flatbed scanner method. This implies that the flatbed scanner method may not capture all of the air voids in conventional concrete that the RapidAir method captures due to the resolution limitations of the scanner.

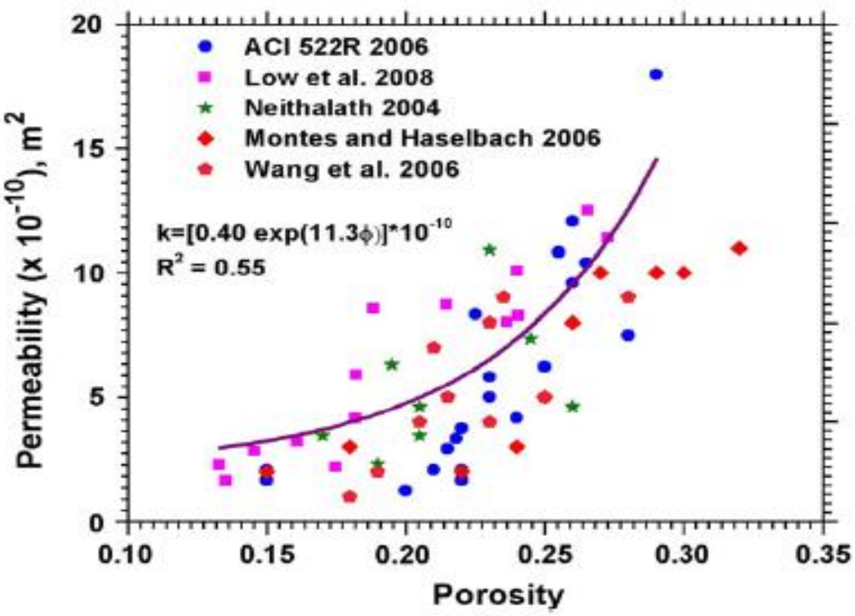
The flatbed scanner method uses an ordinary flatbed scanner to scan the prepared samples. Analysis of the scanned images using a software program provides the air content and spacing factor of the specimens. The flatbed scanner method is cost effective and convenient in comparison to the manual and RapidAir methods of analysis because the scanned image takes a few minutes to produce. The flatbed scanner method can also provide an assessment of the amount and size distribution of entrapped air in concrete (Peterson et al. 2009). Peterson et al. (2009) also reported that in the automated trials the air void frequency and air void specific surface values were slightly lower and the average air void chord length values were slightly higher than those values obtained by the manual method.

Pore-specific Surface Area and Spacing Factor

The specific surface area of a porous material, as given by the total internal boundary between the solid phase and the pore system, is one of the microstructural properties of pervious concrete. The spacing factor is a parameter describing the average distance of an air void to its nearest neighboring air void. The spacing factor is determined using an equation in ASTM C457 (2012) "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete."

Porosity

The porosity of pervious concrete is a function of the concrete materials, their proportions, and the compaction procedures. The typical porosity of pervious concrete ranges from 15% to 30%. Porosity affects the properties of pervious concrete, including compressive strength, flexural strength, permeability, and storage capacity, and is regarded as an important parameter in many design calculations (Montes et al. 2005). Porosity can be measured using the water displacement method proposed by Montes et al. (2005). The relationship between the porosity and permeability of pervious concrete has been discussed in several studies (ACI 2006, Low et al. 2008, Kevern 2006, Schaefer et al. 2006, Montes et al. 2005). Figure 1 shows that permeability increases exponentially with increasing porosity.



Neithalath et al. 2010

Figure 1. Relationship between porosity and permeability for pervious concrete mixtures

Several formulas have been proposed to estimate the permeability of pervious concrete based on the measured porosity. Permeability calculations based on Darcy's Law were found to be less predictable than permeability values estimated using the Carman-Kozeny equation (Kevern et al. 2008, Neithalath et al. 2010, Montes and Haselbach 2006). This is generally due to the flow regime in the pervious concrete, where the flow is transitional rather than laminar, the latter of which is an assumption of Darcy's Law. A summary of some of the best-fit equations describing the relationship between permeability coefficients and porosities is presented in Table 3.

Table 3. Equations predicting permeability coefficients (k) from porosity (ρ)*

Reference	Sample Description	K function of porosity (p)	Carman-Kozeny Equation	
			α factor	Equation
Montes et al. 2005	Porosity: 16%, 18% and 28% Cylinders: 4 in. dia. x 4 in.–6 in. height	$K=7.214*e^{(0.1761*p)}$ $R^2=0.73$ Sample size=19	18.9	$K = 18.9 \times \frac{p^3}{(1-p)^2}$
Delatte et al. 2009	N/A	$K=2.8705*e^{(0.1674*p)}$ $R^2=0.67$	9	$K = 9 \times \frac{p^3}{(1-p)^2}$
Wang et al. 2006	2 Cylinders: 3 in. dia. x 3 in. height Unit Weight: 104.1–132.2 lb/ft^3 Porosity: 14.4%–33.6% Permeability: 0.015–0.193 in./sec	$K=13.257*e^{(0.1579*p)}$ $R^2=0.65$ Sample Size: 19	19	$K = 19 \times \frac{p^3}{(1-p)^2}$
Schaefer et al. 2009, Kevern et al. 2009	Cylinder cores: 3 in. dia. x 3 in. height for permeability Cylinder cores: 3 in. dia. x 6 in. height for porosity test Compaction Level: Low, Regular Unit Weight: 104.1–138.9 lb/ft^3 Porosity: 11.2%–38.8% Permeability: 0.004–0.59 in./sec	$K=5.8826*e^{(0.1873*p)}$ $R^2=0.79$ Sample Size=17	18	$K = 18 \times \frac{p^3}{(1-p)^2}$
Luck et al. 2006	N/A	$K=0.066*e^{(0.1121*p)}$ $R^2=0.79$	43	$K = 43 \times \frac{p^3}{(1-p)^2}$
Huang et al. 2006	N/A	$K=0.732*e^{(0.1451*p)}$ $R^2=0.99$	25.36	$K = 25.36 \times \frac{p^3}{(1-p)^2}$

* Test methods: Falling head permeability test and volume method, units for k (in./sec.) and ρ (%)

Pore Structure

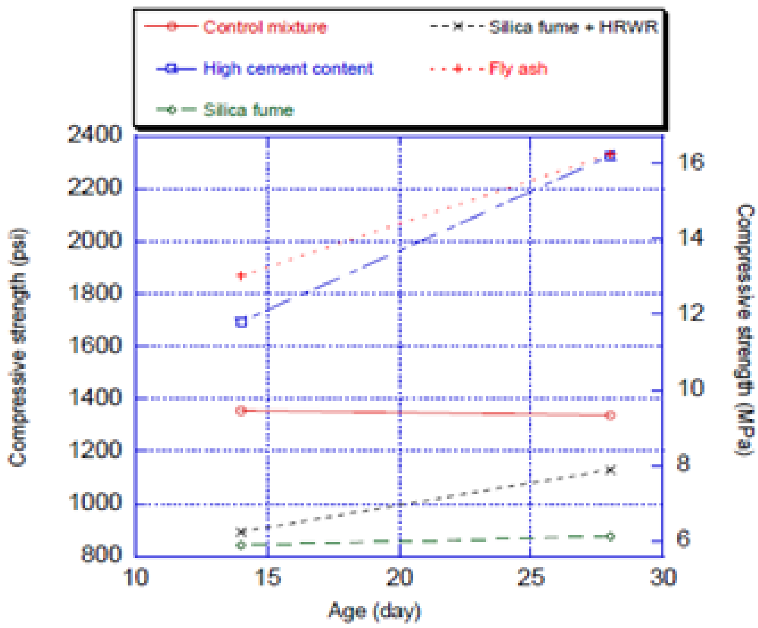
The pore structure of pervious concrete includes the pore volume, pore size, pore distribution, and the connectivity of the pores (Montes et al. 2005, Haselbach and Roberts 2006). Information on pore structure of pervious concrete has been used to understand freeze-thaw damage of pervious concrete, clogging, and associated maintenance and for the prediction of permeability. The effect of pore size distribution on permeability has been studied by several researchers (Neithalath et al. 2010, Low et al. 2008, Kevern 2006). Their results showed that measured porosity is not the only factor that controls the hydraulic performance of pervious concrete, but increasing either the pore size or pore connectivity would also increase the hydraulic conductivity of the pervious concrete.

2.5 Mixture Design Research

Many researchers have experimented with different mixes, cementitious materials, w/b ratios, and additives to obtain the optimal mix design for specific targeted pervious concrete properties. Neithalath et al. (2010) obtained a porosity of about 20% using single-sized coarse aggregate (pea gravel) (#8, #4, or 3/8 in.), Type 1 ordinary Portland cement, a w/c ratio of 0.33, and an a/b ratio of 5. Wang et al. (2006) evaluated pervious Portland cement concrete mixes made with various types and amounts of aggregates, cementitious materials, fibers, and chemical admixtures. Their results indicated that pervious concrete made with single-sized coarse aggregates generally had high permeability (0.57 in./sec) but did not have adequate strength. They found that adding fine sand at approximately 7% by weight of total aggregate improved the compressive strength by 47% while at the same time maintaining adequate water permeability. They recommended a w/b ratio of 0.27 or lower. They also found that adding a small amount (1.5 lb/yd^3) of fiber (polypropylene) to the mix increased the concrete strength as well as the void content, while adding latex (styrene butadiene rubber) at a weight percent of 1.6 improved concrete cracking resistance. Kevern (2006) showed that narrowly graded coarse aggregate between 3/8 in. and 3/4 in. (9.5 mm to 19 mm) produced significant differences in properties compared to conventional concrete. In addition, angular aggregates produced pervious concrete with a lower density, higher void content, higher permeability, and lower strength than concrete that used rounded aggregates. Sumanasooriya and Neithalath (2011) found that using mixture proportioning methods with higher paste contents and lower compaction efforts or with lower paste contents and higher compaction efforts resulted in porosities close to the design porosities in the range of 10% to 27%. They also found that pervious concrete with less paste content resulted in an increase in porosity and pore connectivity. Lian and Zhuge (2010) obtained a 28 day compressive strength of 5802 psi (40 MPa) and a water permeability of 283 in./hr (2 mm/s) using quarry sand at 18% by weight of the mix and an optimum w/c ratio of 0.32. They recommended that when the structural strength or potential clogging of the pores is of particular concern over the pavement's service life, a higher w/c ratio (0.36) could be used.

Several researchers showed that mineral additives such as fly ash, slag, and silica fume resulted in an improvement in the mechanical strength and durability of the concrete (Maso 1996). Improvements in the mechanical properties with the addition of minerals are due to the improved interfacial transition zone (ITZ) between the aggregate and the cement matrix.

Application of a superplasticizer as a dispersion agent has been shown to enhance strength sufficiently to make high-strength porous concrete. Inclusion of silica fume was found not to be very effective in improving the strength of porous concrete due to the difficulty in dispersing the silica fume (Lee et al. 2011). Joung (2008) also investigated the addition of silica fume to a mix and found that the compressive strength decreased primarily due to workability problems, which did not allow the cement paste to uniformly coat the aggregates (see Figure 2). As shown in Figure 2, the addition of fly ash was found to increase the compressive strength of the mix.



Joung 2008

Figure 2. Effect of cementitious materials on compressive strengths

A summary of various studies showing the effects of different mixes on the properties of pervious concrete is given in Table 4.

Table 4. Pervious concrete properties of various mixes

Cement (lb/yd^3)	Coarse aggregate (lb/yd^3)	Fine aggregate (lb/yd^3)	Water-to-cement ratio	Porosity (%)	Density (lb/ft^3)	Permeability coefficient (in./hr)	Compressive strength (psi)	Flexural strength (psi)	References
450-700	- -	- -	0.27-0.34	15-25	100-125	288-770	500-3000	150-550	Tennis et al. 2004
- -	- -	- -	- -	20-30	118-130	- -	2553-4650	561-825	Beeldens 2001
486-600	2500-2700	168	0.22-0.27	18.3-33.6	104.1-130.9	142-694	1771-3661	205-421	Wang et al. 2006
347-944	2112-2836	- -	0.33	19-27	-	- -	1000-2988	- -	Sumanasooriya and Neithalath 2011
- -	- -	- -	0.28-0.36	7.5-16.6	120-140	564-1791	2320-4133	- -	Lian and Zhuge 2010
296	2245	225	0.29	14.8-25.9	108-125	283-1700	- -	- -	Tong 2011

2.5 Pollutants in Stormwater

The use of pervious concrete in pavements has several advantages, such as stormwater runoff attenuation, ground water recharge, retention of natural drainage patterns, minimal water quality degradation, and less need for curbs and storm sewers (ACI 2006). As permeable pavements, pervious concretes have also been described as “effective in-situ aerobic bioreactors” and “pollution sinks” (Scholz and Grabowiecki 2007). Pervious pavement systems are viewed as a sustainable approach to providing needed pavement surfaces for urban areas and, at the same time, allow for natural water infiltration or recharge into the soils.

In general, the extent of contamination of stormwater tends to vary based on land use, with a higher degree of contamination in manufacturing areas and a lesser degree of contamination in residential areas. Stormwater runoff from places such as gas stations, vehicle maintenance shops, and industrial manufacturing plants tend to have both inorganic and organic pollutants of an anthropogenic nature. Many of the pollutants are associated with the solid particles, dust, and debris found on the surface of the pavement. A good example is metal ions, which are generally bound to particles or dust (Magnuson et al. 2001). Particles in the runoff are generally retained and trapped in the pore spaces of the pervious pavements, while some of the pollutants are adsorbed into or interact with the pavement pore surfaces. The subbase and subgrade further provide straining and removal of the particles and pollutants as the water infiltrates through them. Stormwater runoff has been found to contain pollutants such as inorganic pollutants (sulfate, chloride, ammonia, nitrate, and phosphate), metal pollutants (copper and zinc), and organic pollutants (petroleum hydrocarbons) (Dierkes et al. 2002). A list of pollutants and their concentrations in stormwater can be found in Table 5.

Table 5. Pollutants removal in porous pavements

Pollutants		Material	Pavement Type	Conditions	Initial Conc. (mg/L)	Storm water pH	% Removal	Reference
Total Suspended Solids		Concrete	Pervious	Field	N/A	N/A	59	Balades et al. 1995
		Concrete	Pervious	Field	N/A	8.5-10	81	Drake et al. 2014
		Asphalt	Pervious	Field	46	7.4-7.6	81	Pagotto et al. 2000
		Asphalt	Pervious	Field	120	7.1	99	Rossen et al. 2012
		Concrete	Pervious	Lab	475	5.56	89	James and Shaihin 1998
		Concrete	PICP	Field	12	2	33	Bean et al. 2007
COD		Concrete	Pervious	Field	510		89	Balades et al. 1995
BOD		Concrete	Pervious	Lab	2.0	5.56		James and Shaihin 1998
Nutrients	Total Kjeldahl Nitrogen	Asphalt	Pervious	Field	2.1	7.4-7.6	43	Pagotto et al. 2000
		Concrete	PICP	Field	1.03	2	60	Bean et al. 2007
		Concrete	Pervious	Lab	150.6	5.56	99	James and Shaihin 1998
		Concrete	Pervious	Field	N/A	8.5-10	70	Drake et al. 2014
	Total Nitrogen	Concrete	PICP	Field	1.33	2	42	Bean et al. 2007
	Total Phosphorus	Asphalt	Pervious	Field	0.5	7.1	42	Rossen et al. 2012
		Concrete	PICP	Field	0.134	2	63	Bean et al. 2007
		Concrete	Pervious	Field	N/A	8.5-10	9	Drake et al. 2014
Metals	Pb	Asphalt	Pervious				79	Legret et al. 1996
		Concrete	Pervious	Field	0.63	N/A	65	Balades et al. 1995
		Asphalt	Pervious	Field	0.04	7.4-7.6	78	Pagotto et al. 2000
		Asphalt	Basalt + limestone	Lab	21.24	5.5-8.8	88.9	Zhao and Zhao 2014
		Asphalt	Basalt	Lab	21.24	5.5-8.8	87.72	Zhao and Zhao 2014
		Asphalt	Limestone	Lab	21.24	5.5-8.8	91.98	Zhao and Zhao 2014
	Cd	Concrete	Pervious	Field	0.015	N/A	48	Balades et al. 1995
		Asphalt	Pervious	Field	0.001	7.4-7.6	68	Pagotto et al. 2000
	Zn	Concrete	Pervious	Field	1.67	N/A	56	Balades et al. 1995
		Concrete	Gravelpave	Field	N/A	N/A	76	Brattebo and Booth 2003
		Concrete	Grasspave	Field	N/A	N/A	61	Brattebo and Booth 2003
		Concrete	Turfastone	Field	N/A	N/A	77	Brattebo and Booth 2003

Pollutants		Material	Pavement Type	Conditions	Initial Conc. (mg/L)	Storm water pH	% Removal	Reference
		Concrete	Uni Eco-Stone	Field	N/A	N/A	80	Brattebo and Booth 2003
		Concrete	Pervious	Field	N/A	8.6-10	62	Drake et al. 2014
		Asphalt	Pervious	Field	0.228	7.4-7.6	66	Pagotto et al. 2000
		Asphalt	Pervious	Field	0.1	7.1	99	Rossen et al. 2012
		Asphalt	Basalt + limestone	Lab	0.51	5.5-8.8	62.55	Zhao and Zhao 2014
		Asphalt	Basalt	Lab	0.51	5.5-8.8	72.35	Zhao and Zhao 2014
		Asphalt	Limestone	Lab	0.51	5.5-8.8	99.9	Zhao and Zhao 2014
	Cu	Concrete	Gravelpave	Field	N/A	N/A	93	Brattebo and Booth 2003
		Concrete	Grasspave	Field	N/A	N/A	99	Brattebo and Booth 2003
		Concrete	Turfastone	Field	N/A	N/A	89	Brattebo and Booth 2003
		Concrete	Uni Eco-Stone	Field	N/A	N/A	93	Brattebo and Booth 2003
		Concrete	Pervious	Field	N/A	8.6-10	50	Drake et al. 2014
		Asphalt	Pervious	Field	0.03	7.4-7.6	33	Pagotto et al. 2000
	Fe	Concrete	Pervious	Field	N/A	8.6-10	32	Drake et al. 2014
	Mn	Concrete	Pervious	Field	N/A	8.6-10	71	Drake et al. 2014
Hydrocarbons	Total hydrocarbon	Asphalt	Pervious	Field	1.2	7.4-7.6	93	Pagotto et al. 2000
	Motor oil	Concrete	Different paver same as above	Field	N/A	N/A	99	Brattebo and Booth 2003
	Oil and grease	Concrete	Pervious	Field	180	5.6	98	James and Shaihin 1998

PICP = permeable interlocking concrete pavers

Suspended Solids

Total suspended solids (TSS) come from vehicle exhaust emissions, vehicle parts, building and construction materials, and atmospheric deposition of particles. Typical suspended solid sizes range from 0.45 μm to 2 μm, and the typical concentration is 150 mg/L in urban runoff (US EPA 1999b). Drake et al. (2014) investigated the water quality of infiltrate during spring, summer, and fall for three permeable pavement systems (AquaPave, Eco-Optiloc, and Hydromedia) and found that the effluent from all three pavement systems had 80% less TSS than traditional asphalt pavement. Bean et al. (2007) found that the TSS concentration in the exfiltrate of permeable interlocking concrete pavers (8 mg/L) was lower than that of the runoff (12 mg/L).

Metals

Heavy metals are commonly found in stormwater runoff. One of the sources of heavy metals is fine metallic dust generated from the semi-metallic pads of automobile disc brakes. The more common metals found in the metallic dusts are copper and, at times, zinc and lead. A study by Ellis et al. (1987) showed that highway runoff in northwest London was chronically toxic to receiving waters, with the runoff containing Cd, Cu, Pb, and Zn concentrations of 6 ug/L, 45 ug/L, 17 ug/L, and 169 ug/L, respectively. In a study by Davis et al. (2001), the metals and their concentrations in stormwater runoff from various urban areas and highways were typically Zn (20–5000 μg/L), Cu and Pb (5–200 μg/L), and Cd (< 12 μg/L). In these two studies, brake wear was the largest contributor of copper contamination (47% by mass) while tire wear was the largest contributor of zinc contamination (25% by mass) in urban runoff. The fractions of metal elements (particularly Zn and Cu) in the dissolved phase were significantly higher during rainfall events, when the rainfall pH is lowest (3.8) and the average pavement residence time or holding time of the stormwater is relatively long (5.6 min) (Sansalone and Buchberger 1997). Sansalone and Buchberger (1997) indicated that the use of concrete could effectively increase the pH of the runoff. Pratt et al. (1995) reported stormwater pH values between 6.0 and 9.3 for pervious concrete pavers and found that Zn and Cu in the stormwater precipitate out when the pH in the stormwater exceeded a value of 7.

Table 5 presents the percent removal of metals for different permeable pavement systems (Brattebo and Booth 2003, Rushton 2001, Pagotto et al. 2000, Bean et al. 2007). Drake et al. (2014) reported removal efficiencies of Cu (62%, 61%, 50%), Fe (60%, 74%, 32%), Mn (87%, 82%, 71%), and Zn (80%, 82%, 62%) for three commercial permeable pavement systems (AquaPave, Eco-Optiloc, and Hydromedia), respectively. Brattebo and Booth (2003) reported Cu concentrations of 0.89 ug/L, 1.33 ug/L, and 0.86 ug/L and Zn concentrations of 8.23 ug/L, 7.7 ug/L, and 6.8 ug/L in the infiltrates of three permeable concrete pavements (Grasspave, Turfstone, and UNI Eco-stone), respectively, as compared to Cu and Zn concentrations of 7.98 ug/L and 21.6 ug/L in the runoff of impervious asphalt material. For a porous asphalt pavement, Zhao and Zhao (2014) reported 88% and 63% removal of the initial amount of lead and zinc, respectively, in the first flush of stormwater. Bean et al. (2007) found that the Cu and Zn concentrations in the exfiltrate of permeable interlocking concrete pavers (0.005 mg/L and 0.008 mg/L, respectively) were lower than the Cu and Zn concentrations in the influent runoff (0.013 mg/L and 0.067 mg/L, respectively). In summary, for the fours metals commonly found in runoff

(Pb, Zn, Cu, and Cd), higher removals (60% to 90%) were obtained for pervious asphalt and permeable interlocking concrete pavers, while lower removals (about 40% to 60%) were obtained for pervious concrete.

Nutrients

Two common nutrients found in stormwater runoff are nitrogen and phosphorous. The major sources of nitrogen and phosphorus in urban stormwater are from atmospheric deposition and fertilizers found in landscape runoff (US EPA 1999b). Other sources of nutrients include animal and human wastes. Typical concentrations of nitrogen compounds and phosphorus are presented in Table 5.

Bean et al. (2007) compared the concentrations of various pollutants in the exfiltrate from permeable interlocking concrete pavers and standard asphalt systems. For the interlocking pavers, they found that the exfiltrate concentrations of total nitrogen and total Kjeldahl nitrogen (TKN) were 0.77 mg/L and 0.41 mg/L, respectively, which were lower than the surface runoff concentrations of 1.33 mg/L and 1.03 mg/L, respectively, from the asphalt system. However, the nitrate-nitrite concentrations (0.44 mg/L) in the exfiltrate were found to be greater than the concentrations in the runoff (0.3 mg/L). A possible reason is that the aerobic conditions facilitated biological nitrification with the conversion of NH_3-N to NO_2^- -N and NO_3^- -N. Similarly, James and Shaihin (1998) compared the quantity and quality of runoff from permeable interlocking concrete pavers and rectangular concrete pavers with the runoff from an asphalt block. Their study showed that water infiltrating through both interlocking and concrete pavers resulted in an increase in NO_3^- -N (19%) and a decrease in TKN (98%), while there was little change in phosphorous concentrations.

Bean et al. (2007) reported that the total phosphorus concentrations in the exfiltrate for permeable interlocking concrete pavers (0.01 to 0.28 mg/L) were lower than the runoff concentrations (0.03 to 0.98 mg/L). The permeable pavement, as a filtering system, can capture the particulate-bound P in stormwater. However, there is a lack of long-term observations or data to assess whether the bound P would remobilize over time (Drake et al. 2013).

Hydrocarbons

Used motor oil is the most likely source of hydrocarbon contamination in surface runoff (Latimer et al. 1990). According to the US EPA (1996), hundreds of thousands of tons of oil per year were estimated to be in road surface runoff. Motor oils also contain organic chemical additives to enhance the motor oil's performance and metallic compounds produced from the wear and tear of the engine.

Accidental releases or spills of gasoline and antifreeze are common sources of contamination of surface water runoff. Gasoline contains between 10% to 20% of benzene, toluene, ethylbenzene, and xylene isomers (BTEX), which are hazardous substances. In addition, most gasoline contains oxygenated additives such as methyl tertiary-butyl ether (MTBE), which is also a major chemical of concern. Despite being a large source of contamination, low molecular weight hydrocarbons retained on the surface and in the pores of pervious pavement are lost through volatilization and biodegradation (Pitt et al. 1996). Table 5 presents the various studies reporting removal rates for oil and grease, polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons. In summary, oil and grease, PAHs, and petroleum hydrocarbons were attenuated to concentration levels below the detection limits (93% to 99% removal) (Pagotto et al. 2000, Brattebo and Booth 2003, James and Shaihin 1998).

2.6 Removal Mechanisms

Pollutant removal mechanisms include straining/filtering, absorption, adsorption, chemical immobilization, and biodegradation. As the runoff percolates through the porous pavement, solid particles are strained and trapped on the pavement surface and within the pore structure of the pavement (Ferguson 2005). Capture begins with the settling of sand grains and small gravel particles, followed by smaller particles being lodged around the sand grains. Particle capture is one of the processes that can reduce the surface infiltration rate. In this process, particles pass though the surface pores, continue to the bottom of the pavement, and then settle on the pavement's floor or discharge through a drainage pipe, if one is present. Furthermore, most solids accumulate at the surface or the bottom of the pavement, and very limited accumulations tend to be in the middle (Ferguson 2005). Also, metal ions adsorbed onto the particles are removed along with the particles (Magnuson et al. 2001). Due to the solids' retention in the porous material, regular maintenance of the pavement is needed (Legret et al. 1996). Balades et al. (1995) investigated four methods of cleaning porous pavement: moistening following by sweeping, sweeping followed by suction, suction alone, and washing with a high-pressure water jet and suction. The authors found that using a high-pressure water jet with suction produced satisfactory cleaning results.

Dissolved constituents can be removed by adsorbing onto the permeable pavement itself or adsorbing onto solid particles and the solids trapped within the pavement as the infiltrated water travels through the pore spaces (Teng and Sansalone 2004). Calcium, organic acids, PAHs, metals, and phosphorous can be adsorbed onto the suspended solids (Sansalone and Buchberger 2008). Possible immobilization of heavy metals is due to (1) sorption, (2) chemical incorporation (surface complexation, precipitation), and (3) micro- or macro-encapsulation (Glasser 1997). Sorption of heavy metals onto cement hydration products includes physical adsorption and chemical adsorption. Physical adsorption occurs when contaminants are attracted to the surfaces of particles because of the unsatisfied charges of the particles. Chemical adsorption refers to high-affinity adsorption involving covalent bonds. Heavy metal ions may be adsorbed onto the surfaces and then enter the lattice to form a solid phase, which alters the ions' structure or particle size and solubility (Chen et al. 2009). In addition, heavy metals can be precipitated as hydroxides, carbonates, sulfates, and silicates. Hydroxide precipitation for a specific metal occurs when the pH of a solution is raised above an optimum level. The optimum pH is different for each metal and for different valence states of a single metal. Some heavy metals, for example, Zn^{2+}, Cd^{2+}, and Pb^{2+}, form hydroxides and deposit onto calcium silicate minerals (Giergiczny and Krol 2008). Murakami et al. (2008, 2009) found that zinc present on the solid sediments of surface runoff was in the form of free ions and carbonate complexes. Harada and

Komuro (2010) speculated that lead can be immobilized by ettringite, which forms a complex compound as suggested by Gougar et al. (1996).

Organic pollutants trapped and adsorbed in the porous structure may biodegrade due to the microbiota on the pavement (Ferguson 2005). The composition of the microbiota shifts with the seasons. Biodegradation is faster in summer and slower in winter (Ferguson 2005). Transformation of nitrogen compounds and reduction of organic carbon and chemical oxygen demand through pervious pavement have been attributed to microbial activity within the pavement. Pratt et al. (1999) directly found that a highly diverse microbial “biofilm” was visible under an electron microscope. In that study, the geotextile separating the grid setting bed and the aggregate base course was found to be a site for biofilm development. The authors also found that by adding organic material such as peat or carbon granules in the voids of the base aggregate increased the removal of organic pollutants.

3 MATERIALS

3.1 Pervious Concrete Mixes

Four pervious concrete mixes were prepared with a target porosity of 20%. The mix proportions are presented in Table 6. The only differences in these mixes were their binder materials. One mix had pure Portland cement, and the other three had 15% of the Portland cement substituted by fly ash, slag, or limestone powder, respectively.

Table 6. Mix proportions

Sample ID	Mixes	Portland cement (lb/yd^3)	Fly ash (lb/yd^3)	Slag (lb/yd^3)	Limestone powder (lb/yd^3)	Water (lb/yd^3)	Coarse aggregate (lb/yd^3)	Fine aggregate (lb/yd^3)	w/b
Mix 1	Portland cement	639	--	--	--	209	2414	224	0.33
Mix 2	Portland cement -15% Fly ash	543	96	--	--	209	2414	224	0.33
Mix 3	Portland cement -15% Slag	543	--	96	--	209	2414	224	0.33
Mix 4	Portland cement -15% Limestone powder	543	--	--	96	209	2414	224	0.33

For each mix, five concrete cylinders (4 in. diameter x 8 in. length or 100 mm diameter x 200 m length) were cast, along with one 4 in. diameter x 6 in. long (100 mm diameter and 150 mm length) cylinder that was cast within a plastic column for pollution abatement experiments. Three of the 4 in. diameter x 8 in. length cylinders were used for compressive strength tests, while the remaining two were used for permeability (hydraulic conductivity) tests and pore structure characterization experiments.

The coarse aggregate used was granite obtained from Helgeson Quarry, Knife River Corporation, St. Cloud, Minnesota. It had a maximum size of 1/2 in. (12.7 mm), a specific gravity of 2.7, and an absorption of 0.7%. The fine aggregate used was river sand from Hallett Materials, Ames, Iowa. It had a fineness modulus of 2.9, a specific gravity of 2.7, and an absorption of 1.4%. The basic properties and gradations of the coarse and fine aggregates are shown in Table 7.

Table 7. Properties of coarse and fine aggregates

	Coarse aggregate (Granite)		**Fine aggregate (Sand)**	
Unit weight (lb/yd^3)	2563		-	
Specific gravity	2.7		2.54	
Moisture content (%)	1.23		0.47	
Size	No.4		#4 Nominal Maximum Size	
Absorption	0.7%		1.4%	
Void ratio	43%		-	
Gradation	**Sieve (mm)**	**Percent passing**	**Sieve**	**Percent passing**
	12.7	100	3/8 in	100
	9.38	86.9	No.4	97.3
	4.76	14.1	No.8	88.8
	2.38	1.4	No.16	75.3
	1.19	0.8	No.30	48.7
	0.60	0.6	No.50	15.6
	0.15	0.4	No.100	1.1

The chemical and physical properties of the cementitious materials are shown in Table 8.

Table 8. Chemical and physical properties of cementitious materials

Compound (%)	Cement	Fly ash	Slag	Limestone powder
SiO_2	20.2	46.0	36.5	2.82
Al_2O_3	4.7	17.8	8.54	1.06
Fe_2O_3	3.3	18.2	0.83	0.41
SO_3	3.3	2.59	0.6	0.24
CaO	62.9	8.40	41.1	53.3
MgO	2.7	0.95	9.63	0.32
Na_2O	--	0.59	0.29	0.03
K_2O	--	2.16	0.44	0.32
$CaCO_3$	--	--	--	41.92
Loss of ignition (LOI)	1.1	1.49	--	--
Specific gravity	3.15	2.28	2.95	2.70
Blaine fineness (m^2/kg)	385.3	309.7	455.3	390.8

The cement used was a Type I/II Portland cement from Lafarge North America Inc., Des Moines, Iowa. The fly ash was Class F ash from Cumberland Fossil Plant, Knoxville, Tennessee. The slag was a ground granulated blast furnace slag (GGBFS) obtained from Holcim Inc., Des Moines, Iowa. The limestone powder was from Martin Marietta, Ames, Iowa.

3.2 Concrete Mixing and Casting

The concrete was mixed using a Lancaster 30-DH pan concrete mixer. First, coarse aggregate and sand were loaded into the mixer and the materials were dry mixed for 30 seconds. Water was then added to the mixture. After the mixture was mixed for another 30 seconds, the cementitious materials were loaded. The mixture was then mixed for 3 minutes, rested for 3 minutes, and then mixed for 2 more minutes.

After the completion of mixing, the workability of the fresh pervious concrete mixture was evaluated. Then, five 4 in. diameter x 8 in length cylinder specimens and a 4 in. diameter column specimen were prepared. The 4 in. diameter column specimen simulated a 6 in. thick pervious concrete layer of a pervious concrete pavement system on top of a 6 in. thick graded limestone layer (subbase) on top of a 4 in. thick drainable sand layer (as subgrade) (see Figure 5). Each sample was cast with three layers, and each layer was rodded with a 1 in. diameter rod 25 times. After rodding each layer, the samples were vibrated using a vibration table for 5 seconds. Twenty-four hours later, the cylinder specimens were demolded and cured in a standard curing room at 73°F and 98% relative humidity until testing.

3.3 Engineering Properties of Pervious Concrete

For each concrete mix, the key engineering properties were evaluated, including the workability and unit weight of fresh concrete and the compressive strength, air void structure, and water permeability of hardened concrete.

The unit weight of each pervious concrete mix was determined by measuring the weights of the three cylinders divided by their total volume. A 28 day compressive strength test was performed according to ASTM C39 (2003) “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” using a compression testing machine (Test Mark Industries, East Palestine, Ohio). The ends of the cylinders were capped according to ASTM C617 (2015), “Standard Practice for Capping Cylindrical Concrete Specimens.”

The air voids, specific surface areas, and spacing factors of the pervious concrete samples were measured using the RapidAir method and the flatbed scanner method. For both tests, a slice of concrete with dimensions of 4 in. width x 8 in. length x 0.75 in. thickness was cut from each cylinder specimen, and the slice was then cut into half to form two 4 in. width x 4 in. length x 0.75 in. thickness samples, one representing the top section and the other representing the bottom section of the cylinder. These pervious concrete slice specimens were progressively polished with 260 µm, 70 µm, 15 µm, and 6 µm grits using an Allied High Tech Products, Inc. polisher (METPREP 2TM, Rancho Dominguez, California). The polished specimens were then coated with broad-tipped black marker ink. After the ink had dried, the specimens were placed in an oven for 2 hours at 80°C. After the heating, the specimens were removed and coated with a white paste comprised of petroleum jelly and zinc oxide (Fisher Scientific, Pittsburgh, Pennsylvania) and allowed to cool. Any extra paste was removed by dragging an angled razor blade across the surface until all of the paste was removed from the aggregate and cement paste area. Specimens for both tests are shown in Figure 3.

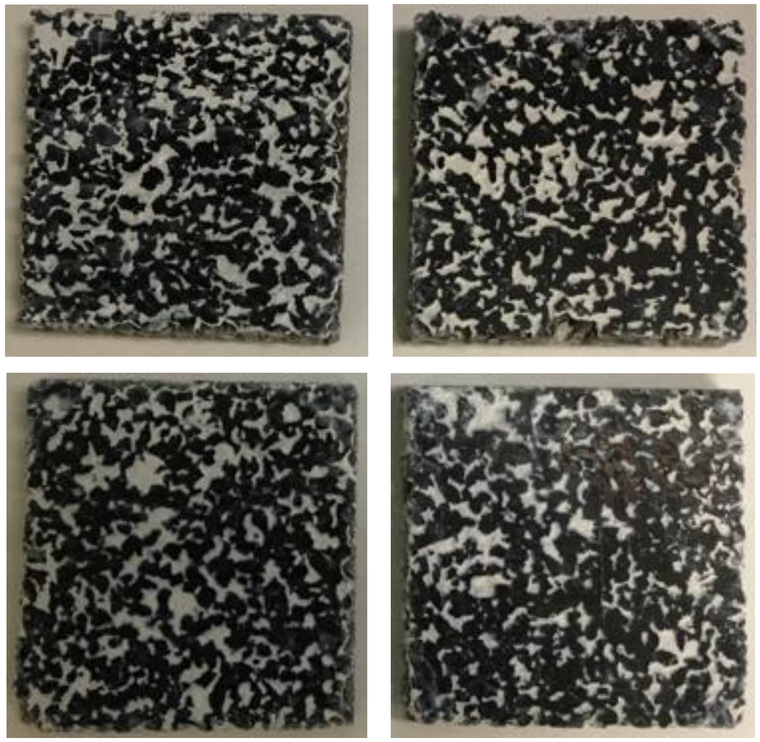


Figure 3. Pervious concrete specimens prepared for air void analysis: Portland cement (top left), Portland cement - 15% Fly ash (top right), Portland cement - 15% Slag (bottom left), and Portland cement - 15% Limestone (bottom right)

For the RapidAir method, the air voids of the specimens were determined using a Rapid Air 457 device from Concrete Experts International (CXI). The specimen was scanned using a video frame with a width of 748 pixels. Up to ten probe lines per frame were used to distinguish between the black and white areas of the specimens. The white-level threshold adjustment further refined the image before void content determination.

For the flatbed scanner method, an office flatbed scanner (Epson Perfection V19 Scanner, Long Beach, California) with a native resolution exceeding 3000 dpi was used. To scan the sample, the specimen was placed on the plate of the flatbed scanner along with a white balance reference card and was scanned at a resolution of at least 3175 dpi. Features approaching 10 microns can be distinguished with minimal interpolation at this resolution. The scanned image was saved in grayscale in TIFF format. Using the ImageJ program (an open source, Java-based image processing program developed at the National Institutes of Health), the white and black intensity modes were determined based on a representative scanned portion of the white balance card. The images were then normalized, and a quarter of the scanned image of the specimen was analyzed using the “Bubblecounter” command in the ImageJ program to estimate the void content, specific surface area, and spacing factor. The parameters used in the image analysis by the ImageJ program are listed in Table 9.

Table 9. Parameters for image analysis

Sample	Paste content	Threshold Air Content	Threshold Void Frequency
Portland cement	0.222	131	110
Portland cement - 15% Fly ash	0.184	120	221
Portland cement - 15% Slag	0.149	129	110
Portland cement - 15% Limestone powder	0.163	131	110

Permeability, or hydraulic conductivity, tests were performed using a falling head permeameter (Montes and Haselbach 2006). Figure 4 shows the permeameter for a 4 in. diameter test specimen.

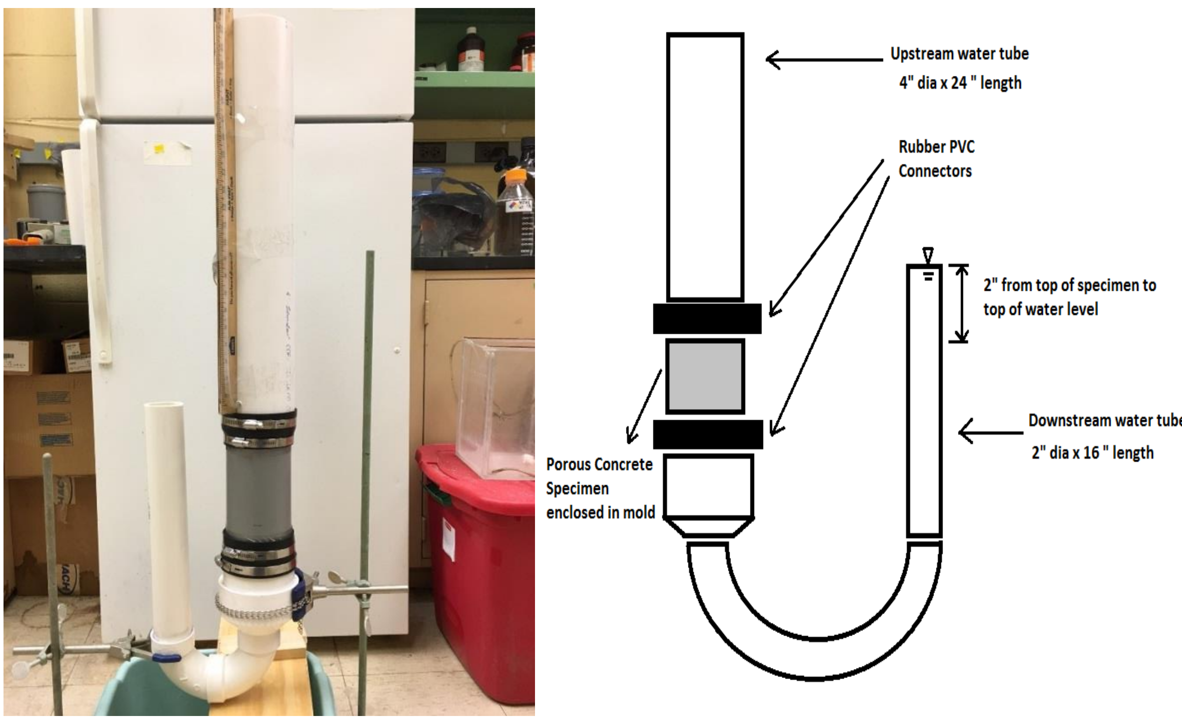


Figure 4. Falling head permeameter: setup (left) and schematic diagram (right)

The permeameter consisted of a 4 in. diameter upstream polyvinyl chloride (PVC) pipe with a U-shaped assembly. The U-shaped assembly was mounted with a scale to record the change in head. To prepare the specimen for testing, the side of the specimen was covered with silicone sealant and wrapped with Saran wrap plastic film before placing in a plastic mold. The gaps between the mold and the top and bottom surfaces of the specimen were sealed with silicone to minimize preferential flow in the space between the mold and the specimen. The mold was then connected to the upstream PVC pipe and a bottom PVC collector pipe with rubber connectors and hose clamps. The height of the end of the U-shaped assembly was kept at 2 in. above the top of the specimen to maintain full saturation of water in the specimen. The apparatus was filled with water from the bottom (downstream side) to displace and expel any air in the specimen. After completely immersing the specimen in water, the apparatus was filled with water continuously from the upstream side until a steady state flow was achieved. At steady state, the water level was recorded. The upstream water level was then increased to a height of 12 in. (Montes and Haselbach 2006) and then allowed to fall by a height of 4 in. The time needed for the water level to fall by 4 in. was recorded.

The saturated hydraulic conductivity was estimated using the following equation (ASTM 2003):

$$K_S = \frac{aL}{A\Delta t} \ln \frac{H_o}{H_t} \tag{1}$$

where K_s is the saturated hydraulic conductivity (in./min), L is the length of the sample (inches), A is the cross-sectional area of the sample (in.^{2}), a is the cross-sectional area of PVC pipe holding the sample (in.^{2}), H_o is initial water head marked at 12 in., and H_t is water head mark at 4 in., and Δt is the time (min) needed for the water level to fall from H_o to H_t.

3.4 Pollution Abatement Column Experiments

To study the pollution abatement properties of pervious concrete, column experiments were conducted. The setup for the column with the different layers is presented in Figure 5.

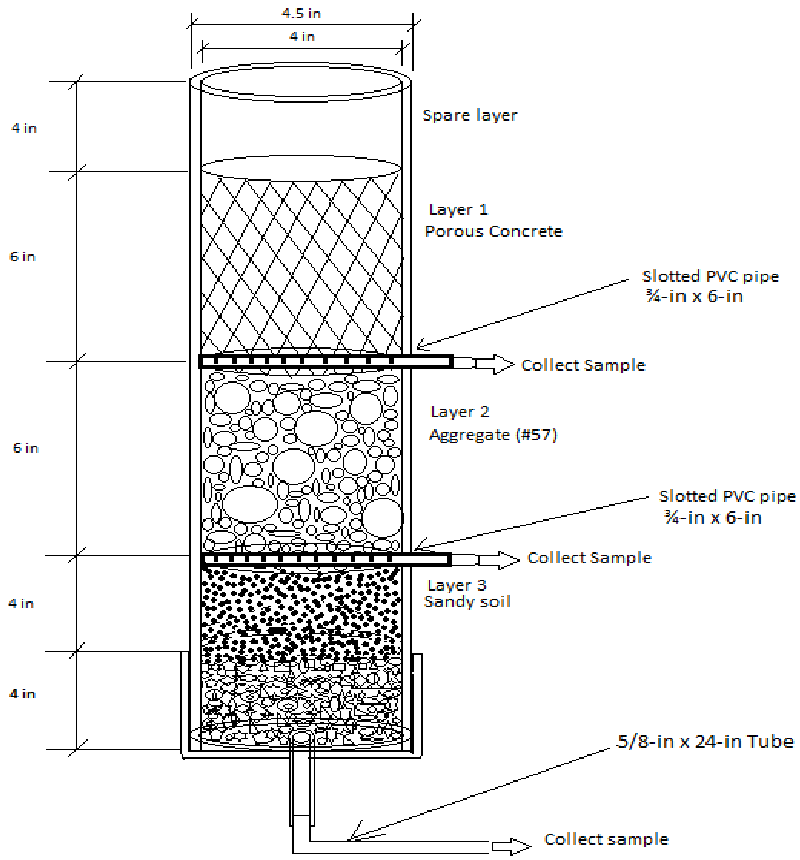


Figure 5. Column setup

The final setup with the simulated rainfall system is presented in Figure 6 along with a photo of the four columns used.

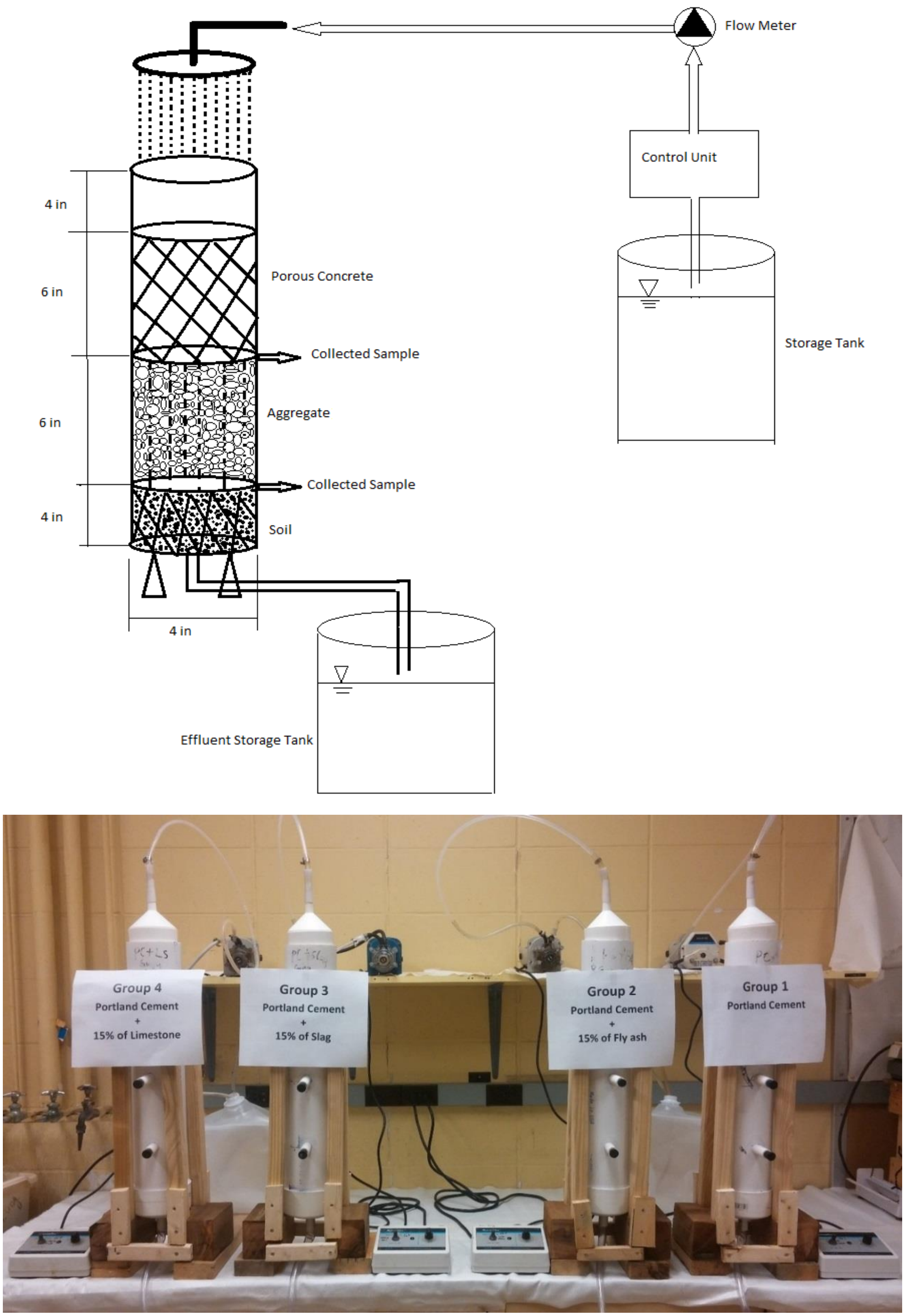


Figure 6. Column test setup with rainfall simulator: simplified flow diagram (top) and test setup (bottom)

The column was made of a 4 in. diameter x 24 in. long PVC pipe with a 4 in. diameter Schedule 40 cap at the bottom. Two 3/4 in. holes were drilled 8 in. and 14 in. from the bottom. In these two holes, a 3/4 in. x 6 in. long PVC pipe with 10 slots spaced at 2/5 in. intervals were inserted for water collection. The 3/4 in. PVC pipe was sealed to the 4 in. pipe with glue. These pipes were connected to a plastic tube with a valve, and the valve was only opened to allow water to be collected when needed. These pipes were identified as the 8 in. and 14 in. water collection pipes. A 3/4 in. hole was drilled in the center of the cap to allow water to be collected from the bottom of the column. The bottom port was always open.

The bottom of the column was covered with a 4 in. diameter steel mesh and filled with gravel (25.0 mm to 4.75 mm) to about 4 in. from the bottom of the column. A tamping rod was used to compact the gravel in the column. This was followed by packing 4 in. of fine-grained sand to serve as the subgrade layer. The 8 in. water collection pipe was then inserted with the slots facing upwards to collect water. Six inches of #57 aggregate was then packed to serve as the aggregate subbase. Similarly, a tamping rod was used to compact the gravel in the column. The 14 in. water collection pipe was inserted into the hole at 14 in. from the bottom of the column with the slots facing upwards. The pipe was placed such that it was covered with a thin layer of gravel. When the concrete mix was ready, 6 in. of the concrete mix was added for the pervious concrete layer. A tamping rod was used to compact the concrete, and the surface of the pervious concrete was made as level as possible.

The simulated rainfall was pumped from a storage tank continuously using a Masterflex pump (Model 7553-02, Cole-Parmer, Court Vernon Hills, Illinois) through a sprinkler placed above the column. At a selected time, infiltrated water samples were collected from the 4 in. and 8 in. water collection pipes and from the bottom of the column.

The pollutant used in the simulated rainwater was naphthalene at a concentration of 30 mg/L. The recommended water quality criterion for naphthalene is 0.5 mg/L. For each column, 3.6 liters of simulated rainwater was applied over a six-hour period. The simulated rainwater applied was equivalent to a 3 in. rain event per hour. This rainfall is similar to the mean rainfall amount of 3.11 in. for a storm period of one hour with a recurrence interval of 100 years in Ames, Iowa, and central Iowa (Iowa DOT 2009). The surface area of the pervious concrete specimen in the column was approximately 12.56 in.^{2}.

After six hours of rainfall, infiltrated water samples were collected from the 8 in. and 14 in. water collection pipes and from the bottom of the column. The water samples were collected in a glass container. For chemical analysis, about 1.5 mL of the water samples were collected from each glass container and placed in a 2 mL glass vial (US EPA 1999a). All samples were refrigerated until they were analyzed. The samples were analyzed using a high-performance liquid chromatograph (HPLC) with a quart pump and an unltraviolet (UV) diode array detector (Model 1200 Series, Agilent Technologies, Santa Clara, California). The column used was a 150 mm × 4.6 mm C18 column. The mobile phase used was 100% (vol./vol.) HPLC-graded water at a flow rate of 1.0 mL/min, and the UV-vis detector wavelength was set at 254 nm. Naphthalene was detected at a retention time of 14 minutes, with a detection limit of 0.01 mg/L. A standard naphthalene curve was prepared using concentrations ranging from 0.1 mg/L to 30 mg/L.

4 EXPERIMENTAL RESULTS

4.1 Workability of Fresh Pervious Concrete

The workability of pervious concrete for four mixtures was evaluated qualitatively based on the ability of the plastic pervious concrete to form a ball by hand. Figure 7 shows the balls made from the mixtures tested.

Figure 7. Workability test results of pervious concrete mixtures: Portland cement (top left), Portland cement - 15% Fly ash (top right), Portland cement - 15% Slag (bottom left), and Portland cement - 15% Limestone (bottom right)

It can be seen from the figure that the pure Portland cement mixture and 15% fly ash mixture had good workability, and sufficient mortar materials filled the spaces among the coarse aggregate particles and held the particles into a well-shaped ball. The 15% slag and 15% limestone powder mixtures had slightly lower workability, and some spaces were clearly seen among some coarse aggregates. However, the workability of all four mixtures tested was acceptable because they all formed a ball.

It should be noted that the specific gravities of fly ash (2.28), slag (2.95), and limestone (2.7) are lower than that of Portland cement (3.15). Therefore, the 15% (by weight) replacement of these materials for cement actually provided more paste volume in the concrete, which could improve the concrete workability. However, the slag had a much higher specific surface value (247 yd^2/lb or 455.3 m^2/kg) and the limestone powder had a slightly higher specific surface value (212 yd^2/lb or 390.8 m^2/kg) than the Portland cement (209 yd^2/lb or 385.3 m^2/kg). As mixing water was adsorbed onto the fine particle surfaces, the workability of the concrete was reduced. As a result, the pervious concrete mixture with 15% slag displayed a less desirable workability than the mixture made with pure Portland cement.

4.2 Unit Weight, Strength and Permeability of Pervious Concrete

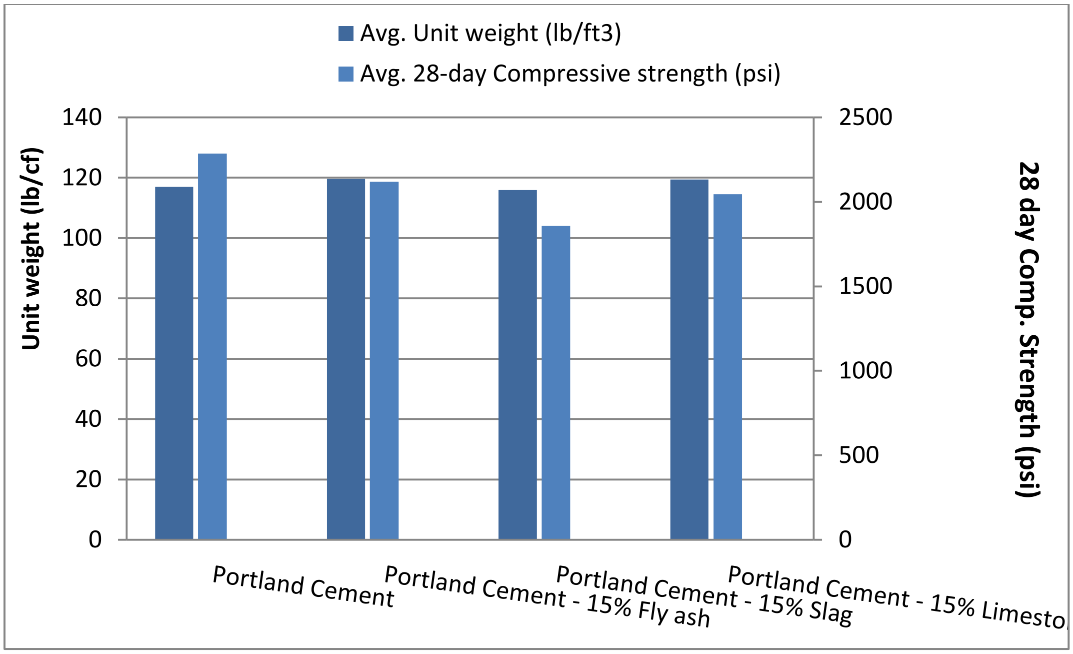
The unit weight, 28 day compressive strength, and water permeability of the four pervious concrete mixes studied are summarized in Table 10.

Table 10. Unit weight, strength, and permeability of pervious concrete mixes

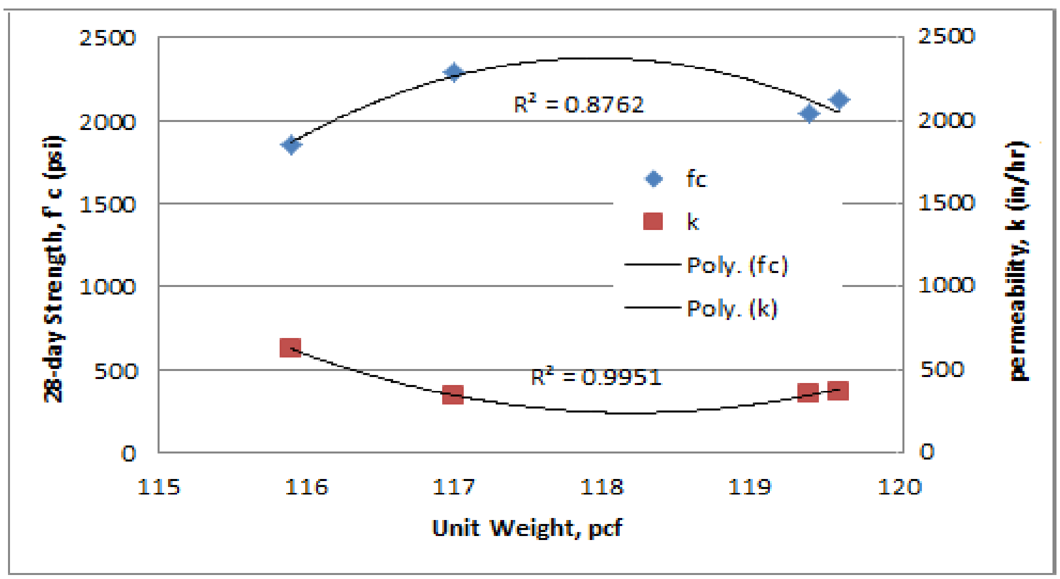
Mixes	Unit weight (lb/ft^3)	28 day compressive strength (psi)	Permeability coefficient, Ks, (in./hr)
Portland cement	117.0	2285 ± 228	340
Portland cement - 15% Fly ash	119.6	2120 ± 207	369
Portland cement - 15% Slag	115.9	1858 ± 184	624
Portland cement - 15% Limestone powder	119.4	2045 ± 344	354

As shown in the table, the unit weights of mixtures made with 15% fly ash and 15% limestone powder replacement were slightly higher than that of the mixture with pure cement, which itself was a little higher than that of the mixture made with 15% slag replacement. This small variation might be related to the workability of the mixtures because they had the same mix proportions. Many studies have indicated that the use of fly ash and limestone powder as a cement replacement can improve concrete workability (Malhotra 2002, Beeralingegowda and Gundakalle 2013), thus possibly helping the consolidation of the concrete.

As shown in Figure 8, the 28 day compressive strength of the four mixes generally increased while the water permeability generally decreased with the unit weight of the concrete.



(a) Comparison



(b) Relationship

Figure 8. Unit weight, strength, and permeability of pervious concrete mixtures

Because the mix with slag had the lowest unit weight value, which probably attributed to the concrete's consolidating ability or workability, its compressive strength was about 10% lower than that of the mix with pure cement due to the former's less desirable consolidation.

The permeability of pervious concrete is mainly controlled by its pore structure (volume, size, and connectivity), the latter of which also significantly affects concrete strength because pores reduce the effective cross-section area for load bearing. Therefore, opposite trends were found in

Figure 8 between the concrete strength versus unit weight and the permeability versus unit weight. These findings are consistent with previous studies, although the data from the present study are limited.

4.3 Pore Structure of Pervious Concrete

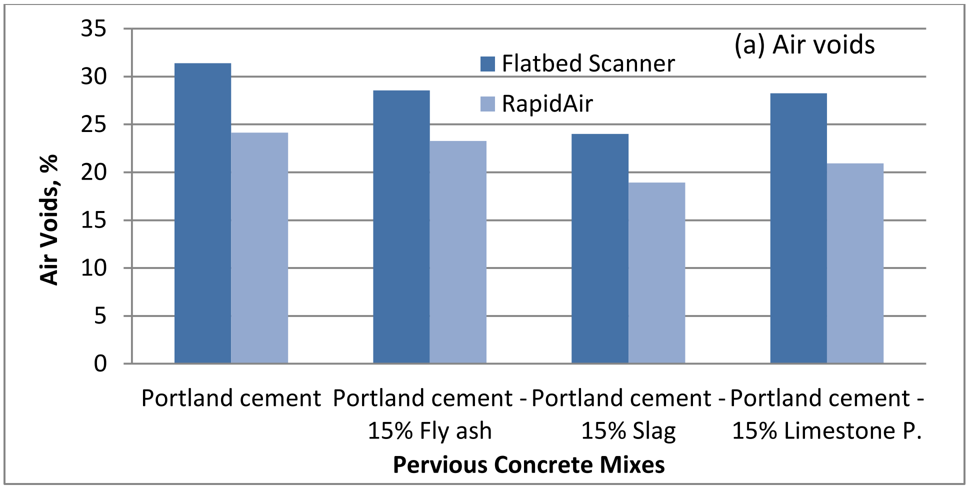
The pore structures of the four pervious concrete mixes used in this study were analyzed using both the flatbed scanner test and the RapidAir test. The RapidAir scanning test method had only 5 traverses for each tested sample, compared to 150 traverses performed by the flatbed scanner test method. The results are presented in Table 11.

Table 11. Pore parameters of pervious concrete mixes

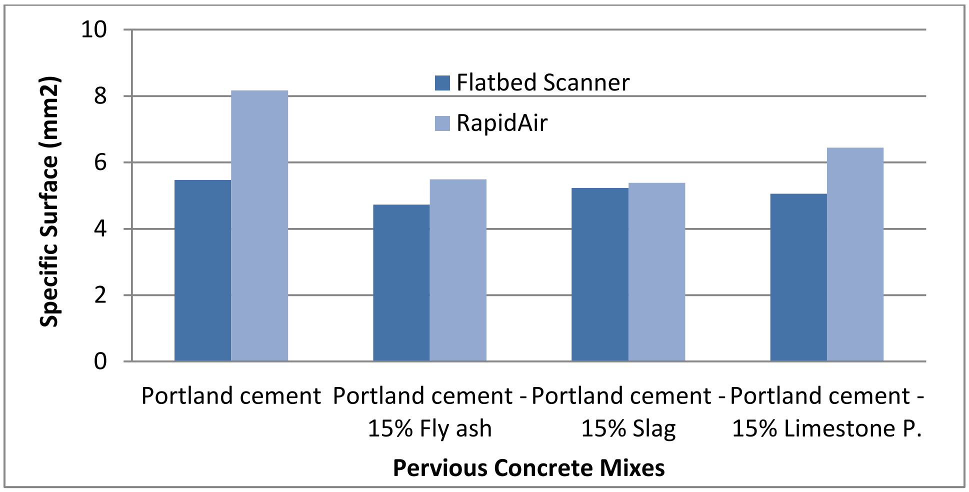
	Flatbed scanner			RapidAir		
Mixes	Void content (%)	Specific surface area (mm^{-1})	Spacing factor (mm)	Void content (%)	Specific surface area (mm^{-1})	Spacing factor (mm)
Portland cement	31.41	5.47	0.130	24.15	8.17	0.11
Portland cement - 15% Fly ash	28.57	4.73	0.137	23.27	5.49	0.15
Portland cement - 15% Slag	24.00	5.23	0.120	18.93	5.38	0.13
Portland cement -15% Limestone powder	28.25	5.06	0.120	20.95	6.45	0.12

Each datum in the table represents the average value of the two (top and bottom) samples cut from a 4 in. x 8 in. cylinder.

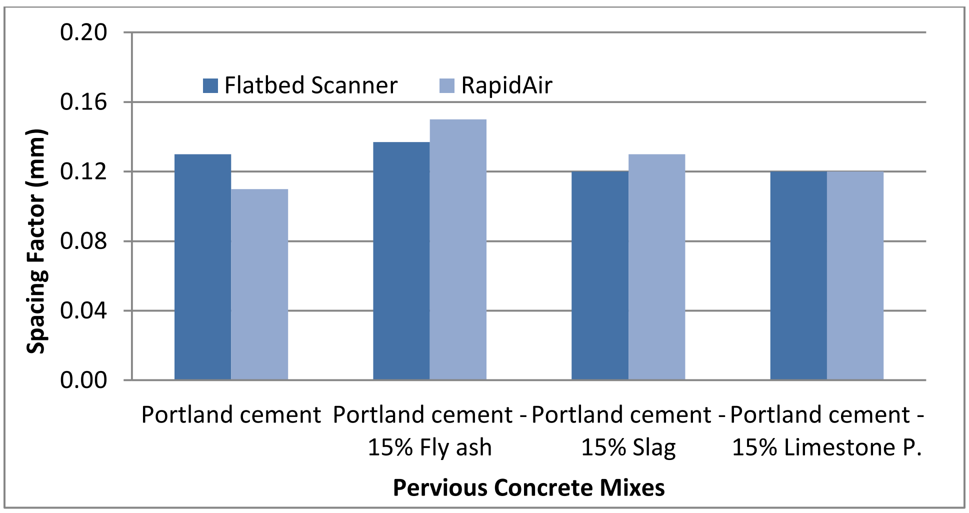
Figure 9 presents the comparisons of the test data obtained from these two different test methods.



(a) Air voids



(b) Specific surface area



(c) Spacing factor

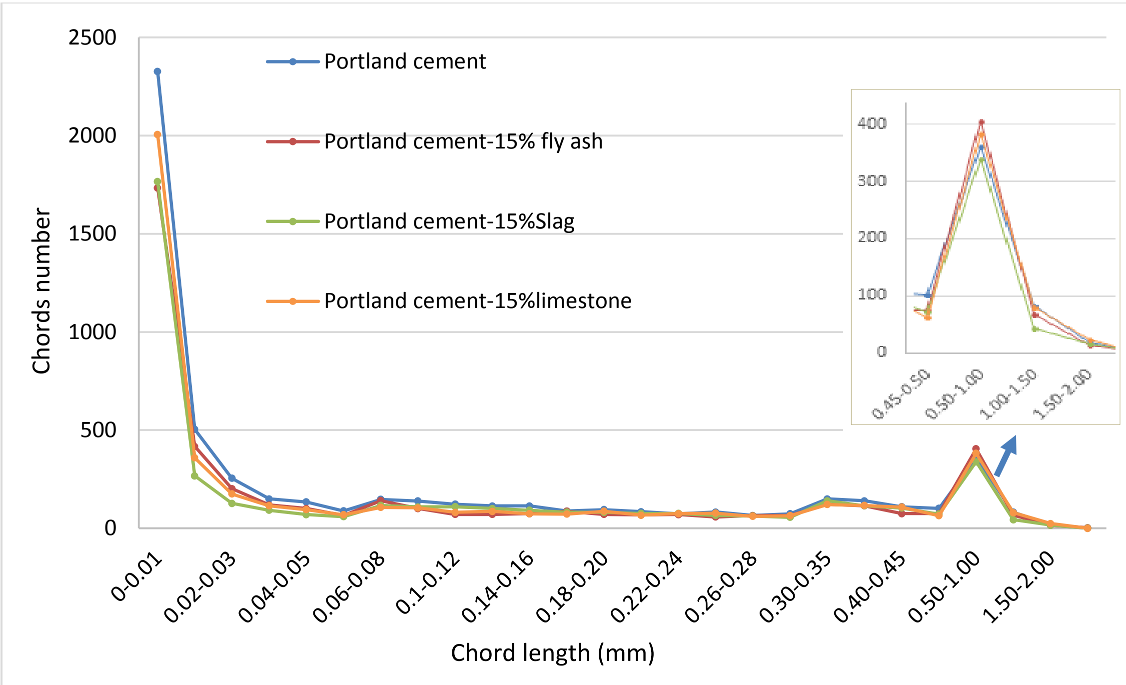
Figure 9. Comparisons of air void parameters obtained from flatbed scanner and RapidAir tests

As seen in Figure 9a, the air void ratios of the four pervious concrete mixes measured by the flatbed scanner method are all higher than those measured by the Rapid Air method, but the specific surface values measured by the flatbed scanner method are all lower than those measured by the Rapid Air method (Figure 9b). This suggests that the flatbed scanner had captured some large voids that were not captured by the RapidAir test method. The microscope camera of the RapidAir method generally was unable to capture voids larger than 3 mm but was able to capture smaller voids than the flatbed scanner test due to the good resolution of the microscope camera, resulting in a higher specific surface area than that measured by the flatbed scanner test method.

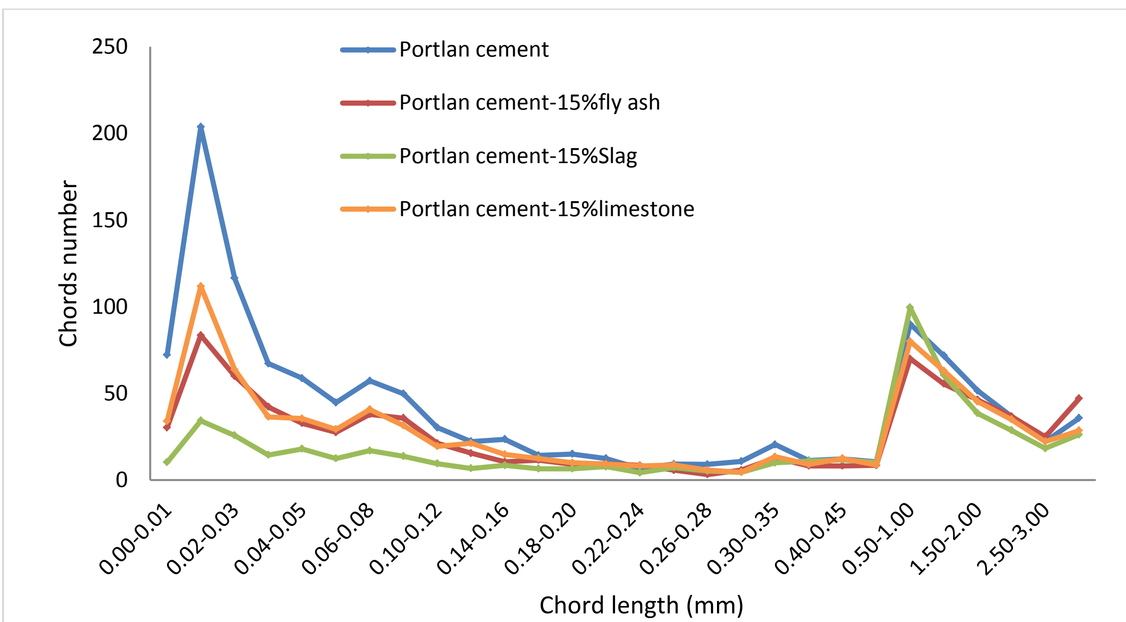
Note that the mixes made with 15% fly ash and 15% limestone powder replacement for cement have lower void contents than the mix made with pure cement. This is to be expected due to the higher paste content and better workability of the fly ash and limestone powder mixes. However, it is not clear why the mix made with 15% slag replacement has the lowest void ratio, as indicated by both the flatbed scanner and RapidAir test methods, because its unit weight and strength were also slightly lower than those of the other mixes. Further study is needed.

The spacing factor indicates the distance from an air void to the nearest neighboring air void. Figure 9c shows that the spacing factor values of the four mixes studied ranged from 0.12 to 0.137 mm, which are all acceptable in pervious concrete practice. However, there is no clear trend in the spacing factors measured by the flatbed scanner and RapidAir test methods. This is possibly related to the different ranges of the air void sizes measured by these two different methods. In addition, the RapidAir scanning test method had far fewer traverses for each tested sample than the flatbed scanner test method.

To further elucidate the pore structure of the pervious concrete mixes, Figure 10 provides the size distribution of the voids measured using the flatbed scanner and the RapidAir methods, respectively.



(a) Flatbed scanner



(b) RapidAir

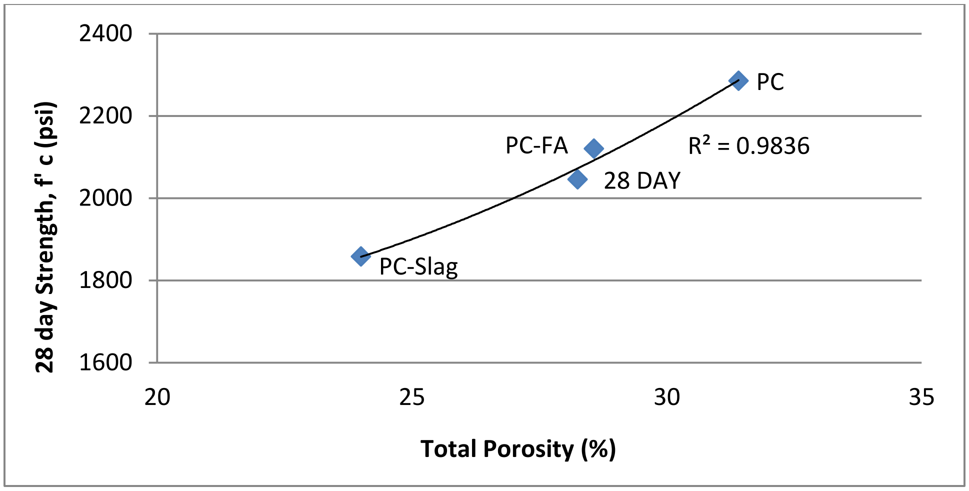
Figure 10. Void distribution curves obtained from flatbed scanner and RapidAir methods

In Figure 10a, the chord length represents the pore/void size, and the number of the chord length represents the number of pores/voids in the tested samples. As mentioned previously, the flatbed scanner test method had many more traverses than the RapidAir test method, and therefore the chord number obtained from the flatbed scanner method is much higher than the chord number obtained from the RapidAir method.

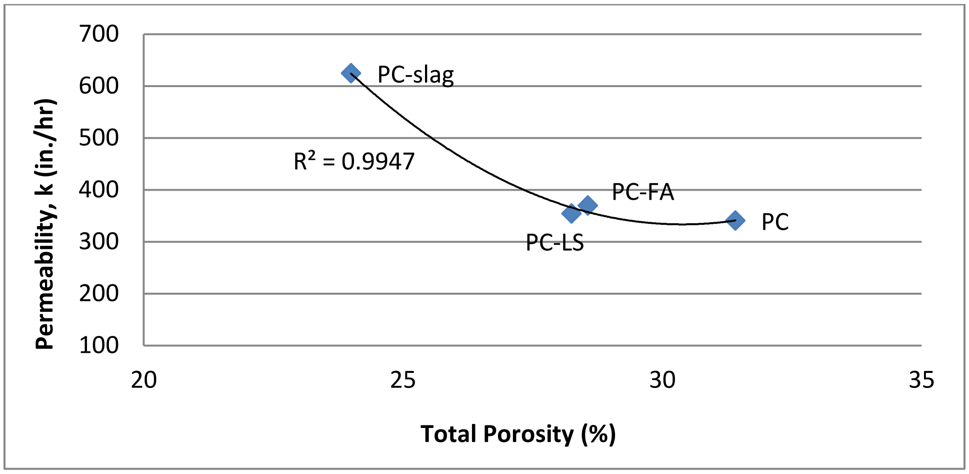
As seen in Figure 10, both the flatbed scanner and RapidAir test results show that there were two major groups of air voids in the pervious concrete: one group had sizes in the range of 0.01 mm to 0.03 mm, and the other had sizes in the range of 0.5 mm to 3.0 mm. The group with the small-sized air voids represents the voids in the cement paste/mortar, which might control the pollution removal mechanism, while the group with large-sized air voids represents the voids among the aggregate particles, which might contribute significantly to the water permeability of the concrete. (Note that although the flatbed scanner method captured air voids larger than 3 mm, there was difficulty in identifying the number of voids with sizes larger than 3 mm. A reason was that when the computer characterized the chords separated by grayness on a traverse, only the continuous pixels with the same grayness (white or black) were counted as one chord. If any dark pixels existed, even a small gray spot in the white paste that was used to fill the voids for image analysis, these darker pixels were identified as the end of the white chord. Thus, actually large voids were read as small voids and false results were provided. This testing error did not have significant effects on the total air porosity but significantly affected the size distributions of the air voids. Therefore, the number of air voids with sizes less than 3 mm is not reported in Figure 10a.)

Figure 10 also illustrates that both the flatbed scanner and RapidAir test results show that replacing cement with 15% fly ash, slag, or limestone powder decreased the amount of the more numerous group of voids (those from 0.01 mm to 0.03 mm) in the cement paste/mortar. The quantitative difference may be caused by the number of traverses characterized by these two methods. In addition, the quality of the image scanned by the flatbed scanner was greatly related to the resolution of the scanner, and some small air voids might not have been identified due to the limited resolution of the scanner. On the other hand, the RapidAir method read the sample features with a microscope camera, and some errors might have been introduced by the scale of the camera lens. For materials having large voids, such as pervious concrete, the flatbed scanner test method is preferred because the RapidAir test method does not capture voids larger than 3 mm.

Many researchers have studied the effects of voids on the strength and permeability of pervious concrete (Lian et al. 2011, Alaica et al. 2010). Although limited tests were performed in the present study, similar effects were found, as illustrated in Figure 11.



(a) Compressive strength



(b) Permeability
(PC = Portland cement; FA = fly ash; LS = limestone powder)

Figure 11. Effects of porosity on strength and permeability of pervious concrete

The figure indicates that the total porosity obtained from the flatbed scanner test is closely related to the pervious concrete's strength and permeability. (Note that similar but weaker relationships also exist if the total porosity obtained from the RapidAir test is used.)

4.4 Pollutant Abatement Experiments

The results of the pollution abatement experiments are presented in Tables 12 and 13. Table 12 provides the water volume balance for the experiments.

Table 12. Water volume balance

Volume	Control (distilled water only)			Polluted water (naphthalene = 30 mg/L)		
	Volume Added (L)	Volume collected over 6 hours (L)	Volume collected from 6 to 18 hours (L)	Volume added (L)	Volume collected over 6 hours (L)	Volume collected from 6 to 18 hours (L)
Portland cement	3.60	3.20	0.352	3.60	3.48	0.063
Portland cement - 15% Fly Ash	3.60	3.30	0.250	3.60	3.49	0.051
Portland cement - 15% Slag	3.60	3.30	0.252	3.60	3.50	0.051
Portland cement - 15% Limestone powder	3.60	3.56	0.035	3.60	3.52	0.015

Water was collected over a 6 hour period, and any water remaining 12 hours later was also collected. For all mixes, the total volumes of water collected for the control experiment and the polluted water experiment were similar to the volumes added to the column. This shows that only a small volume of water was retained in the column.

Table 13 shows the naphthalene concentrations in the water samples.

Table 13. Naphthalene concentrations in water samples

Mixes	Water Samples	Control Conc. (mg/L)	Naphthalene Conc. (mg/L)	Percent Removal (%)
Portland Cement	Rainwater	0	29.25	--
	14 in. collection pipe (after pervious concrete)	0	26.31	10
	8 in. collection pipe (after subbase)	0	16.28	44
	Bottom (after subgrade)	0	14.99	49
Portland Cement - 15% Fly Ash	Rainwater	0	30.72	--
	14 in. collection pipe (after pervious concrete)	0	21.49	30
	8 in. collection pipe (after subbase)	0	20.15	34
	Bottom (after subgrade)	0	16.24	47
Portland Cement -15% Slag	Rainwater	0	29.84	--
	14 in. collection pipe (after pervious concrete)	0	29.70	0.5
	8 in. collection pipe (after subbase)	0	16.16	46
	Bottom (after subgrade)	0	9.81	67
Portland Cement - 15% Limestone	Rainwater	0	30.72	--
	14 in. collection pipe (after pervious concrete)	0	21.49	30
	8 in. collection pipe (after subbase)	0	20.15	34
	Bottom (after subgrade)	0	16.24	47

The control experiment using distilled water showed that the pervious concrete, subbase, and subgrade materials did not contain any naphthalene. When water with naphthalene was added, the percent naphthalene removal through the pervious concrete was about 30% for mixes with fly ash and limestone powder. Only 10% of the naphthalene was removed by the mix with Portland cement only. In the case of the mix with slag, only 0.5% of the naphthalene was removed. This low removal percent may be due to the high hydraulic conductivity found for this mix, where water was rapidly channeled through the pervious concrete mix because the pores were continuously connected from the surface to the bottom of the specimen. This condition probably resulted in minimal surface contact and interaction between the water and the materials of the mix.

Because the subbase and subgrade materials used were the same for all specimens, one would expect the percent removal through the subbase and subgrade materials to be similar. However, this was not the case, with different percent removals through the subbase/subgrade for different columns. The highest percent removal was 67% for the mix with slag. The fly ash and limestone powder mixes and the cement-only mix showed about 47% to 49% removal of naphthalene. It is possible that the water flow path through the subbase and subgrade may play a role in exposing the surfaces of the materials for the removal of naphthalene.

5 CONCLUSION

In this study, four pervious concrete mixes made with pure Portland cement and with 15% cementitious materials (slag, limestone powder or fly ash) as a Portland cement replacement were investigated. Their physical properties, such as workability, unit weight, compressive strength, water permeability, and air void structures, were characterized. Four laboratory-scale column experiments were conducted to assess the pollutant attenuation properties of the pervious concrete mixes. The following conclusions can be drawn:

1. All four pervious concrete mixtures studied had acceptable workability (i.e., formed a ball shape by hand). The workability of the mixtures made with pure Portland cement and 15% fly ash replacement appeared to have better workability than those mixtures made with 15% slag and 15% limestone powder replacement.

2. The unit weight of the fresh pervious concrete mixtures ranged from 115.9 lb/yd^3 to 119.6 lb/yd^3, with the mixture with 15% slag being the lowest (115.9 lb/yd^3), followed by the pure cement mixture (117.0 lb/yd^3), then the mixture with 15% limestone powder (119.4 lb/yd^3), and finally the mixture with 15% fly ash (119.6 lb/yd^3).

3. The 28 day compressive strength of the pervious concrete mixes ranged from 1858 psi (mix with 15% slag) to 2285 psi (pure cement mix). The compressive strength generally increased with unit weight and decreased with total porosity (air void ratio).

4. The water permeability of the pervious concrete mixes ranged from 340 in./hr (pure cement mix) to 642 in./hr (mix with 15% slag). The permeability generally decreased with unit weight and increased with total porosity (air void ratio).

5. The total porosity (or air void ratio) of the pervious concrete mixes ranged from 24.00% (mix with 15% slag) to 31.41% (pure cement mix) as measured by the flatbed scanner test method. The total porosity ranged from 18.93% (mix with 15% slag) to 24.15% (pure cement mix) using the RapidAir method. It was not clear why the concrete porosities were not correlated to their unit weights. Further study is needed.

6. The total porosities of the four pervious concrete mixes measured by the flatbed scanner method were all higher than those measured by the RapidAir method, but the specific surface areas measured by the flatbed scanner method were all lower than those measured by the RapidAir method. The flatbed scanner might have captured some large voids that were not captured by the RapidAir test method. Using a microscope camera, the RapidAir device is generally unable to capture voids larger than 3 mm. However, due to the good imaging resolution of the microscope camera, the RapidAir test method might have captured a larger quantity of small voids. In its ability to capture large voids, the flatbed scanner test method has a clear advantage over the RapidAir test method for pervious concrete. However, the flatbed scanner may also capture the background aggregate particles in some large voids and

make false identifications regarding the size of these voids. Further study is needed to further improve this test method.

7. The pollutant abatement experiments showed that the mixes with fly ash and limestone powder removed about 30% of the influent naphthalene concentration. The mix with pure cement removed 10% of the influent naphthalene concentration, while the mix with slag removed only 0.5% of the influent naphthalene concentration. The water volume balance showed that less than 1% of the water added was retained in the experimental column setup.

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