Development of a Special Provision on the Use of Pervious Concrete As a Stormwater Management Tool in Parking Lots

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Final Report VTRC 18-R15

Standard Title Page—Report on State Project

Report No.: VTRC 18-R15	Report Date: November 2017	No. Pages: 31	Type Report: Final Contract	Project No.: RC00098
			Period Covered:	Contract No.:

<table>
<tr>
<td colspan="4">Title:

Development of a Special Provision on the Use of Pervious Concrete As a Stormwater Management Tool in Parking Lots</td>
<td rowspan="3">Key Words:
Pervious concrete, stormwater, strength, abrasion resistance, density, voids, infiltration rate, hydraulic conductivity</td>
</tr>
<tr>
<td colspan="4">Author(s):
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<tr>
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Sponsoring Agencies' Name and Address:
Virginia Department of Transportation
1401 E. Broad Street
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Supplementary Notes:

Abstract:

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The purpose of this study was to develop a special provision for the Virginia Department of Transportation for the implementation of pervious concrete as a stormwater management tool through the exploration of mix designs, material properties, and infiltration capabilities. The special provision is provided in the Appendix.

The study recommends that the Virginia Department of Transportation begin using the special provision developed in this study as an option when permeable pavements are determined to be the proper stormwater best management practice for the parking lot in question.

FINAL REPORT

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

November 2017
VTRC 18-R15

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Each contract report is peer reviewed and accepted for publication by staff of Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

The abundance of impervious surfaces in developed areas leads to increased threats from stormwater runoff. The contaminants carried in unmanaged stormwater runoff in addition to higher volumes of water damage the natural environment and put undue stress on ecosystems on which society depends for both recreation and industrial activities. Pervious concrete makes it possible to replace surfaces that generate stormwater runoff with permeable surfaces while maintaining the original function of the impermeable surface (such as a parking lot).

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INTRODUCTION

Effective management of stormwater runoff (SWR) in urban areas, or rainwater and snowmelt that is unable to percolate into the ground, is a significant concern for civil engineers because of the risks it poses to both the natural environment and humans (U.S. Department of Commerce, 2016; U.S. Environmental Protection Agency [EPA], 2016a). Areas that tend to generate high volumes of SWR include roads, roofs, and lawns (EPA, 2016a). In addition to harmful pollutants, high volumes of SWR can also cause flooding, which incurs great cost to urban infrastructure and can also erode urban and rural streams (Ahiablame et al., 2012; Winston et al., 2016). Recent developments in SWR have pushed the field toward low impact development, the intention of which is to mimic the means by which natural systems manage stormwater by intercepting the water before it leaves the area (EPA, 2016b). One particular type of low impact stormwater management is permeable pavement, or pavement through which stormwater is able to percolate (Ahiablame et al., 2012). The three types of permeable pavement most commonly used are interlocking pavers, porous asphalt, and pervious concrete (PC) (University of Maryland, 2016). In terms of highest permeability, reasonable price, and longest service life, PC is argued to be the most desirable of the three (University of Maryland, 2016).

According to a study conducted by the Wisconsin Department of Transportation, permeable pavements, including PC, are capable of removing 80% to 85% of total nitrogen, 30% of nitrate, and 98% of metals (Wisconsin Department of Transportation, 2012). The Virginia Department of Environmental Quality (2013) stormwater design specification No. 7 identifies total mass removal rates for nitrogen and phosphorus to be 81% (using Level 2 design). With porosities typically ranging from 15% to 30%, PC hydraulic conductivity is in the range of 5.5×10^{-3} to 4.6×10^{-1} in/s (19 to 1,400 in/hr) (Montes and Haselbach, 2006). The highly porous

nature of PC, caused by the omission or large reduction in the amount of fine aggregates from the mixture, is what allows the infiltration and contaminant capture of SWR (National Ready Mixed Concrete Association [NRCMA], 2004).

The basic mix design of PC consists of cementitious materials, coarse aggregate, water, and very little (if any) fine aggregates (NRMCA, 2004). The American Concrete Institute (ACI) has published a design reference on PC for proper handling and placement (ACI Committee 522, 2013). With the water–cementitious materials ratio typically between 0.35 and 0.45 (some have reported 0.25 to 0.35), the concrete is able to maintain its workability without the paste becoming too runny and filling the voids (NRMCA, 2004; Putman and Neptune, 2011). Generally, coarse aggregates are uniformly graded at a 3/8 in size (Anderson et al., 2013). Fine aggregates are typically omitted from PC mixes as they have a tendency to fill voids (NRMCA, 2004). However, some have included sand in small amounts to the benefit of strength, freeze-thaw resistance, and impact and abrasion resistance (Amde and Rogge, 2013; Kevern et al., 2015). Explorations into the inclusion of dispersed fibers have provided mixed results, with some indicating increases in tensile strength, but factors such as paste quality, type of fiber, length of fiber, and quantity of fiber greatly influence the benefits (Thakre et al., 2014).

In a PC stormwater management system, there is the pavement and the storage area; the storage area has loose aggregates beneath the top layer of PC (NRMCA, 2004). Pavement thickness (the top layer) varies depending on predicted load while the thickness of the lower layers of loose aggregate is dependent on the volume of SWR to be stored (Henderson and Tighe, 2012). PC pavement design should include sufficient storage space such that the water is able to evacuate the concrete, avoiding saturation and preventing freeze-thaw damage (NRMCA, 2004). NRMCA (2004) reports the recommended depth of loose aggregate beneath the concrete as 8 to 24 in.

There were no applications of PC by the Virginia Department of Transportation (VDOT) when this study was initiated, though there were dozens of lots in Virginia that had been implemented by non-VDOT entities such as localities and private developers. PC can be used in low-volume traffic conditions such as in rest areas, park and ride lots, and shoulders (ACI Committee 522, 2013). VDOT has more than 40 rest areas and more than 300 park and ride lots, which would be viable candidates for PC applications (VDOT, 2013, 2016). Development of a special provision would enable VDOT to place PC at its facilities.

PURPOSE AND SCOPE

The purpose of this study was to introduce PC as a stormwater management tool to VDOT for use in areas with low traffic volumes, initially the parking lots. To do so, a VDOT special provision on PC was required. The special provision, completed in April 2016, was based on a literature review, field observations from two Fairfax County (non-VDOT) projects, and analyses done in the laboratory of the Virginia Transportation Research Council (VTRC). In the laboratory, small batches of concrete, 0.5 ft^3, were prepared and tested. Observations of PC

placement and performance were carried out in Fairfax County at the Stringfellow Park and Ride Lot and the Reston District Police Department parking lot.

METHODS

The method for developing the special provision consisted of conducting a literature review, field observations, and laboratory analyses. Field observations were conducted at two parking lot projects in Fairfax County, Virginia. Using lessons learned from the field placement observations in addition to a review of the literature, laboratory analyses of PC were then conducted in the VTRC laboratory, initially using the mix designs from the field observations and then exploring other designs. The culmination of the field observations and laboratory work was the special provision on the use of PC as a stormwater management tool. Table 1 lists the laboratory tests used in the development of the special provision.

ASTM C1688, ASTM C1754, ASTM C1701, and ASTM C1747 were all developed specifically for PC specimens. ASTM D5084, originally developed to test soil samples, and ASTM C39, to test non-PC, were adapted for PC applications.

Table 1. Test Procedures for Pervious Concrete

Test	ASTM Method
Density and void content – fresh concrete (ASTM, 2013)	C1688
Density and void content – hardened concrete (ASTM, 2015b)	C1754
Infiltration rate (ASTM, 2015a)	C1701
Impact and abrasion resistance (ASTM, 2015c)	C1747
Hydraulic conductivity	D5084
Compressive strength (ASTM, 2004)	C39

Field

Placements

The intention of observing the Fairfax projects at the Stringfellow Park and Ride lot and the Reston District Police Department parking lot was to gain an understanding of the fundamental requirements of proper PC placement. The same contractor (with NRMCA's Pervious Concrete Craftsman certification) conducted both placements. Ready mixed concrete plants, using the same ingredients from the same sources and located no more than a 20-minute drive from each location, provided the concrete. The mix used at both locations is described in Table 2. Diabase traprock (nominal maximum size 3/8 in) with an SSD relative density of 2.98 and a dry rodded unit weight of 111 lb/ft^3 was used for the coarse aggregate.

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Table 2. Concrete Mix Design Used in Fairfax County Projects

Material	lb/yd^3
Portland cement	550
No. 8 coarse aggregate	2972
Water	182
Water/cementitious ratio (w/cm)	0.33
Air Entraining Admixture (oz/cwt)	1
WR+R[a] (oz/cwt)	10
Void content (%)	19.7
Fresh concrete density (lb/ft^3)	137.2
Theoretical air-free density (lb/ft^3)	170.8

[a] WR+R: Type D water-reducing and retarding admixture with enhanced paste rheology and hydration control.

The NRCMA's Pervious Concrete Craftsman Certification Program uses ACI 522.1-10 as the specification for placement procedures (ACI Committee 522, 2013). A conveyor belt moves the concrete from the ready mixed concrete trucks to the lots for placement. Once the PC is in place, a vibrating roller and a non-vibrating roller are used in perpendicular directions for consolidation and finishing. A bladed roller with a 1 3/4 in blade put the joints in the concrete at spacing of 12 ft. Within 20 minutes of placement, the curing process must begin, so the concrete is covered by a black polyethylene sheet immediately following the jointing.

At the Stringfellow and Reston lots, conventional asphalt is used in the driving lanes and PC is used in the parking stalls. The volume of voids in PC is specified as 20%, and the pavement thicknesses are not less than 6 in. Directly beneath the concrete is loose, washed aggregate of variable depth (approximately 2 ft thick) of which less than 1% could pass a No. 200 sieve. The top layer is 1 to 2 in of No. 8 aggregate, which is directly above the No. 2 aggregate. The No. 8 and No. 2 aggregate layers are individually compacted by a 10-ton static roller passing at least 4 times. At the bottom of the loose aggregate is No. 57 stone, which surrounds a 6-in-diameter perforated underdrain pipe. In these projects, the pipe facilitates the evacuation of water from the subbase to a storage tank or an area where infiltration into the ground can occur. Figure 1 shows the process of construction. The pipe is necessary because infiltration into the soils beneath PC is assumed to be inconsequential. A non-woven polypropylene geotextile filter fabric is located beneath the loose aggregate to prevent the fines of the underlying soil mixing with the loose aggregate storage layer and potentially clogging the system.

Figure 1. Construction Sequence at the Stringfellow Lot (L-R: Perforated Pipe Being Placed in the Loose Aggregate; Two-Directions of Rolling Compaction; Joints Being Placed)

Field Specimens

Cylindrical concrete field specimens of 12- or 18-in diameter and a 6-in height were made from the fresh concrete at each jobsite to explore the impact of specimen size on infiltration rate testing. It was hypothesized that the lateral flow in the specimen after the water passed through the 12-in-diameter infiltration ring would influence the infiltration rate results.

Consolidation methods for the Stringfellow lot and Reston lot field specimens varied to obtain different density and voids. Table 3 presents the various compaction methods used on the PC field specimens collected from the Stringfellow lot. The intention for collecting these specimens was density testing and infiltration rate testing. After 7 days in the field covered with plastic, the specimens were moist cured in the laboratory up to 1 month. This was assumed to be the wet density. For 1 week, the specimens were then allowed to dry in a relative humidity of 50%, after which the dry density was recorded. The average void content (determined using the theoretical density) of 18% falls within the target range of 15% to 25%. The target value of 20% and the range were identified through the literature review and correspondence with the PC contractors at the sites.

Table 4 presents the various compaction methods used on the PC specimens collected from the Reston District Police Department parking lot. The same mix design as was used at Stringfellow was used at Reston even though the compaction methods differed slightly. The average void content of the Reston samples was lower than that of Stringfellow, though not far out of the 15% to 25% target range. An increase in the pressure applied during compaction is likely the cause of this decrease in average void content.

After curing at the jobsites for 7 days, the specimens were brought back to the VTRC laboratory for final curing in the moist room. These specimens were used for hardened density tests and infiltration rate testing in the VTRC laboratory.

Table 3. Stringfellow Project Compaction Methods and Resulting Density and Void Contents of Field Specimens

No.	Diameter (in)	Compaction	Wet Density (lb/ft^3)	Dry Density (lb/ft^3)	Voids (%)
1	12	Tamped with hand float and finished with hand float	138.5	137.3	19.6
2	12	Tamped with hand float and finished with hand float	137.5	136.2	20.2
3	12	Hand float finish	144.6	143.4	16.1
4	12	Proctor 20 drops per layer; two layers	145.4	143.9	15.8
5	18	Hand float finish	139.5	137.3	19.6
6	18	Proctor 80 drops one layer	144.7	141.9	16.9
Average			141.7	140.0	18.0

Table 4. Reston Project Compaction Methods and Resulting Density and Void Contents of Field Specimens

No.	Diameter (in)	Compaction	Wet Density (lb/ft^3)	Dry Density (lb/ft^3)	Voids (%)
1	12	One layer with hammer plus roller	150.0	148.5	13.1
2	18	One layer with hammer plus roller	144.4	143.1	16.2
3	12	Two layers with hammer plus roller	148.2	147.2	13.8
4	18	Two layers with hammer plus roller	149.8	147.7	13.5
5	12	Proctor 40 drops per layer; two layers; roller	152.9	150.6	11.8
Average			149.1	147.4	13.7

Infiltration Rates and Visual Observations

Monitoring the infiltration rates of the parking lots is done through multiple methods. One option is observation wells, holes in the pavement that allow a view of the water that has failed to drain from the system. Once 18 to 30 hours after a significant rainfall of 0.5 to 1 in has passed, the wells are inspected to ensure that the water has drained satisfactorily. Another method is ASTM C1701, which requires water to be poured onto the pavement through a ring secured by plumber's putty to the pavement surface. To investigate how well the lots survived their first winter, the summer after placement, lots were visually observed and testing in accordance with ASTM C1701 was carried out on several locations within each lot.

VTRC Laboratory Work

Infiltration Rate

The specimens were kept at the jobsite to cure for 7 days under plastic covering, after which they were brought back to the VTRC laboratory for infiltration rate testing. Infiltration rates of the 12-in and 18-in-diameter field specimens made from the concrete collected from the Stringfellow and Reston projects were measured in accordance with ASTM C1701 (ASTM, 2015a). The procedure consists of the following steps:

1. With plumber's putty, secure the infiltration ring to the surface of the cylindrical concrete specimen.

2. Pour 8 lb of water into the concrete specimen, keeping the water level between the two parallel black lines running approximately 0.5 in above the ring edge, and record the time it takes for all of the water to leave the surface of the specimen.

3. If the time from Step 2 is greater than 30 seconds, repeat Step 2 with another 8 lb of water. If the time from Step 2 is less than 30 seconds, repeat Step 2 but use 40 lb of water.

4. The conversion chart on the infiltration ring converts the time of infiltration of the 40 lb pour to infiltration rate or the formula given in ASTM C1701 can be used.

5. In the case that the infiltration was slow and 8 lb was used for the second pour, find the time of infiltration on the chart and divide the corresponding rate by 5. This gives the rate for 8 lb of water.

Mix Designs

A sample of the coarse aggregates was brought back from Stringfellow to be used in the VTRC laboratory batch mixtures. The mix design from the Stringfellow project was used for the first laboratory mixture at VTRC and is denoted Batch 1 in Table 5. The only difference between Batch 1 and the mixture used at Stringfellow is that the portland cement, though it was the same type, was sourced from a different manufacturer. As in the field projects, the w/cm ratio was kept constant at 0.33 throughout all batches. Mix designs with varying proportions of portland cement, coarse aggregate, and water contents were explored in the other 15 batches shown in Table 3 with the purpose of obtaining void contents of 15% to 25%. Batch 5 and Batch 10 included small amounts of sand to explore the impact of sand on void contents. Specimens cast from 16 batches presented in Table 3 were used for the density, strength, abrasion resistance, and hydraulic conductivity analyses outlined in the following sections. Compaction of the 16 batches was performed in accordance with the respective test method discussed in the following sections.

Table 5. VTRC Laboratory Batches

Batch	Date	PC lb/yd^3	No. 8 CA lb/yd^3	Water lb/yd^3	w/cm
1	9/23/15	550	2972	182	0.33
2	12/7/15	660	2725	216	0.33
3	12/7/15	570	2884	188	0.33
4	12/14/15	700	2884	231	0.33
5*	12/14/15	600	2884	129	0.31
6	12/14/15	492	2784	162	0.33
7	12/15/15	674	2933	223	0.33
8	12/15/15	544	2933	180	0.33
9	12/15/15	414	2933	137	0.33
10*	12/15/15	600	2933	198	0.33
11	12/17/15	648	2983	214	0.33
12	12/30/15	700	2884	231	0.33
13	12/30/15	410	2946	135	0.33
14	1/20/16	388	2983	128	0.33
15	1/20/16	700	2884	231	0.33
16	1/20/16	544	2933	180	0.33

PC = portland cement; * Batch 5 included 129 lb/yd^3 sand and Batch 10 included 173 lb/yd^3 sand.

Fresh Density and Void Content

Density and void content of fresh PC was measured in accordance with ASTM C1688 (ASTM, 2013). This test allows the use of either the standard Proctor hammer or the Marshall

hammer. For this study, the standard Proctor hammer was used. The procedure to determine fresh density and void content followed these steps:

1. Calculate the volume and take the mass of the bucket. In the VTRC laboratory, the air meter bowl was used.

2. Place one layer of concrete at a depth little over half of the bucket height.

3. Compact the first layer and apply 20 blows from the Proctor hammer.

4. Place the second layer, allowing the concrete to rise just above the bucket edge.

5. Compact the second layer with 20 blows from the Proctor hammer.

6. Ensure that the surface of the concrete is flush with the bucket edge.

7. To calculate fresh density, divide the mass of the specimen (excluding the mass of the bucket) by the volume of the bucket.

8. Determine theoretical density, or the density of the specimen as if it were free of air voids.

9. To calculate percent voids, take the difference between the theoretical and measured density values, divide that difference by the theoretical density, and then multiply by 100.

Hardened Density and Void Content

Density and void content of hardened PC was measured in accordance with ASTM C1754 (ASTM, 2015b). The following steps were taken to determine the density and void contents of the hardened specimens:

1. Test specimens are to be 4 in diameter and 8 in height.

2. Dry the specimens at 100 °F for 24-hour increments, recording each specimen's mass after each time increment until the mass change is less than 0.5%. Record the final mass.

3. Submerge each specimen for 30 minutes, tapping with hammer to release air bubbles.

4. Record the mass of each submerged specimen.

5. Use Equation 1 to determine hardened density:

$$Density = \frac{K*A}{D^2*L}$$ Eq. 1

$$K = 2,200 \ (in - lb \ units)$$
$$A = dry \ mass \ of \ the \ specimen(lb)$$
$$D = average \ diameter \ of \ specimen(in)$$
$$L = average \ length \ of \ specimen(in).$$

6. Use Equation 2 to determine void content of the specimen:

$$Void \ content = \left(1 - \frac{K*(A-B)}{\rho_w*D^2*L}\right) * 100 \hspace{2cm} \text{Eq. 2}$$
$$B = submerged \ mass \ of \ the \ specimen(lb)$$
$$\rho_w = water \ density \ of \ bath(lb/ft^3).$$

Compressive and Tensile Strengths

ASTM C39, originally intended for conventional concrete, was used to measure the compressive strength of PC (ASTM, 2004). Sample dimensions were 4 in in diameter with an 8-in height. Consolidation of these cylinders consisted of 5 drops of the standard Proctor hammer on each of the two layers.

ASTM C496, also originally intended for conventional concrete, was used to measure the splitting tensile strength of concrete (ASTM, 2011). Splitting tensile strength is calculated using Equation 3.

$$T = \frac{2*P}{\pi*l*d} \hspace{2cm} \text{Eq. 3}$$

$$P = maximum \ applied \ load \ as \ indicated \ by \ machine(lb)$$
$$l = specimen \ length(in)$$
$$d = specimen \ diameter(in).$$

Impact and Abrasion Resistance

Resistance to impact and abrasion is measured using the procedure outlined in ASTM C1747 (ASTM, 2015c). The procedure consists of the following steps:

1. Record the mass of three 4-in-diameter, 4-in-high PC specimens.

2. Place the three specimens in the barrel of the Los Angeles machine with no steel balls.

3. Allow the machine to tumble for 500 revolutions.

4. Record the mass of concrete that is held on a 1 in sieve.

5. Subtract the amount of material left behind from the initial mass, divide by the initial mass, and then multiply by 100 to get the percent mass loss.

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Hydraulic Conductivity

The specimens used to determine hydraulic conductivity of the PC were 4 in in diameter and 6 in in height; the top and bottom 1 in from 4 x 8 in specimen was cut off to eliminate the end effects. In the field, the end effect is expected to be less since the confinement is less rigid than the lab cylinder and there is no impact loading by the hammer. Figure 2 shows the falling head permeameter used to calculate hydraulic conductivity. The falling head permeameter was constructed in the VTRC laboratory and was based on ASTM D5084, a soils test (ASTM, 2016).

Figure 2. Falling Head Permeameter for Hydraulic Conductivity

The following steps were taken to determine the hydraulic conductivity of the specimens:

1. Cover the sides of the cylinder with shrink wrap.

2. Place the cylinder in the tube on the left side of the permeameter, and secure with the seals.

3. Open the valve on the right and fill the permeameter with water from the right side such that the concrete specimen is saturated and water is approximately 10 mm above the concrete surface.

4. Once the specimen is saturated, close the valve and pour water into the left side to a height of 10 in above the specimen.

5. Open the valve and record the time the water takes to drop a distance of 8 in.

Recovery After Clogging

The falling head permeameter was also used to study the PC's behavior when clogging materials were introduced to the system. A solution consisting of 20 g of clay, 20 g of sand, and 2 L of water was introduced to each specimen and the resulting infiltration rates were examined in accordance with the following procedure:

1. Follow the hydraulic conductivity procedure using clean water; record this as Time 1.

2. Follow the hydraulic conductivity procedure except replace the clean water in Step 3 with clogging solution; do not record time.

3. Follow the hydraulic conductivity procedure using clean water; record this as Time 2.

4. Keeping the specimen in place, vacuum the top surface of the specimen with a shop vacuum.

5. Follow the hydraulic conductivity procedure using clean water; record this as Time 3.

6. Remove the specimen, power wash and vacuum it again, and replace it in the permeameter.

7. Follow the hydraulic conductivity procedure using clean water; record this as Time 4.

RESULTS AND DISCUSSION

The results of testing the field specimens from the two field sites and the laboratory specimens are described in this section. Specifically, the results of the field observations were the density values and the condition of the concrete after 6 months while the results of the laboratory analyses include infiltration rates, fresh and hardened concrete density, strength, impact and abrasion resistance, hydraulic conductivity, and recovery after clogging.

The average void content of the field specimens was 18%, as shown in Table 4 for the Stringfellow project. The average falls within the target range of 15% to 25%, as was determined through the literature review and correspondence with the PC contractors at the sites. The average void content for the Reston project specimens was 13.7%, as shown in Table 5; it was much lower than that obtained from the Stringfellow project specimens, which had less compactive effort without the roller.

The Stringfellow and Reston lots were placed during the fall and winter of 2015-2016. The following summer (2016), both sites were visited to inspect visually the quality of the concrete after one winter of use and to determine the infiltration rates. The lots were visually inspected to assess if physical defects were present. Observations indicated asphalt raveling in the area of the joints where the asphalt driving lanes met the PC stalls. ASTM C1701 testing was performed at both the Stringfellow and Reston lots to determine infiltrations rates. Figure 3 shows the procedure being performed at the Stringfellow lot. The test indicated high variability in infiltration capabilities (21 to 820 in/hr) of the concrete even within a few feet of the other testing areas.

The infiltration test values are summarized in Table 6. More than two-thirds of the test values were above 100 in/hr, which is considered satisfactory (Wisconsin Department of Transportation, 2012). Lower infiltration rates tended to be seen closer to the joints; this may be because of clogging near the joint by raveling asphalt and the possible difference in compaction near the edge.

Figure 3. Quality Check of Concrete at Stringfellow the Summer After Placement (Same Procedure Followed at Reston)

Table 6. Infiltration Rates

Site	No.	Infiltration Rate (in/hr)
Reston	1	102
	2	78
	3	42
	4	35
	5	21
	6	168
	7	164
	8	214
	9	185
	10	441
	11	470
Stringfellow	12	820
	13	597
	14	37
	15	201
	16	181

VTRC Laboratory Work

Infiltration Rate

The infiltration rate testing was conducted in the laboratory on the field specimens made from the Stringfellow and Reston concrete. Three additional laboratory specimens were cast in the laboratory following the same mix design as the field placements and compacted by a roller. Figure 4 shows the results of ASTM C1701 testing for the 10 specimens with a 12-in diameter. The varying void contents were created as a result of variations in compaction efforts, not in variations of mix designs, even though changes in mix design also result in changes in void contents.

$y = 12.7e^{0.2x}$
$R^2 = 0.82$
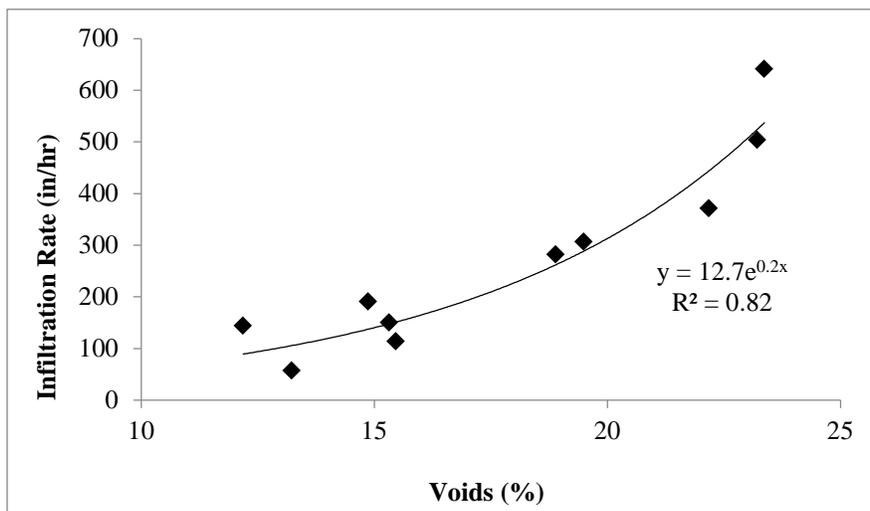
Figure 4. Results of ASTM C1701 Testing, Infiltration Rates (in/hr) Plotted Against Void Content (%)

Mix Designs

Table 7 summarizes the exploratory mix designs used in the VTRC laboratory. Design density refers to the density anticipated strictly from the mix design. Theoretical density refers to the density if there were no air voids in the concrete. Measured density refers to the density of the fresh concrete measured in accordance with ASTM C1688. It was found that the mix designs were influential in changing porosity values.

Table 7. VTRC Laboratory Mixtures and Their Corresponding Density Values and Void Contents

Batch	Voids (%)	Density (lb/ft³)			Measured Voids (%)
		Design	Theo.	Meas.	
1	19.7	137.2	170.8	126.4	26.0
2	19.7	134.9	166.4	136.4	18.0
3	19.7	134.9	168.6	134.4	20.3
4	15	141.3	166.2	138.4	16.7
5	16.7	140.7	168.9	138.4	18.1
6	25	127.4	169.8	131.2	22.7
7	15	141.9	166.9	140.0	16.0
8	20	135.4	169.3	130.8	22.7
9	25	129.0	172.0	131.2	23.7
10	13.6	144.6	167.4	138.8	17.1
11	15	142.4	167.5	136.2	18.7
12	15	141.3	166.2	144.0	13.4
13	25	129.3	172.3	127.2	26.2
14	25	129.6	172.8	129.2	25.2
15	15	141.3	166.2	145.6	12.4
16	20	135.4	169.3	136.4	19.4

Fresh and Hardened Density and Void Content

Results for the fresh and hardened density testing of the laboratory specimens are explained in this section. Figure 5 shows the results of the fresh density testing with the design density (the density predicted by the mixture) on the y-axis and the measured density (the density measured by ASTM C1688) on the x-axis. The linear regression indicates that measured density is correlated to design density about half of the time.


$$y = 0.7x + 38.8$$
$$R^2 = 0.54$$
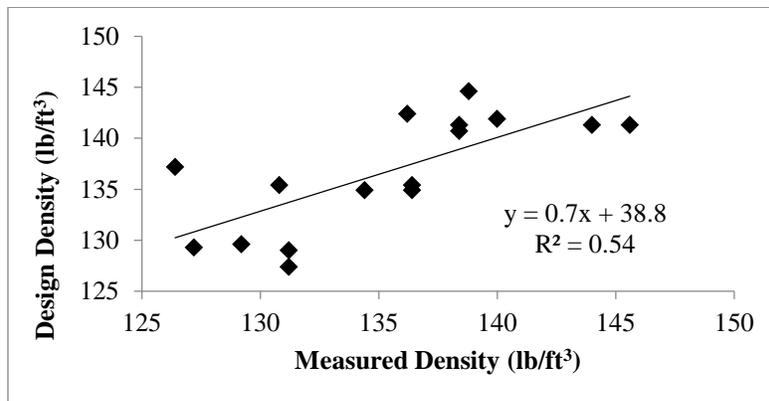
Figure 5. Design Density as a Function of Measured Density (lb/ft³)

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Figure 6 gives the results of the hardened density tests (determined in accordance with ASTM C1754) as they relate to the cement content of the mixture. As cement content increases, void content correspondingly decreases. Linear regression analysis showed a strong correlation of 0.78 between the void content and the cement content.


$$y = -0.04x + 40$$
$$R^2 = 0.78$$
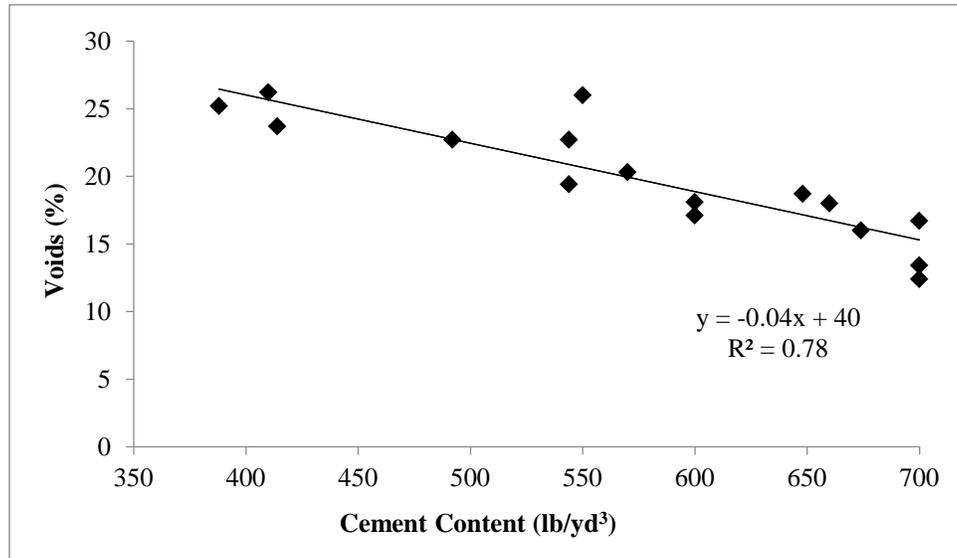
Figure 6. Voids (%) As a Function of Cement Content (lb/yd^3)

Compressive and Tensile Strengths

Strength testing for PC is not a test performed for quality assurance because the distribution of voids related to consolidation causes high variability in strength results. However, compressive strength and tensile strength tests were still performed since the same consolidation was applied to the specimens. Figure 7 shows the relationship of compressive strength and measured density. The correlation coefficient was good.

$$y = 139.7x - 16408$$
$$R^2 = 0.83$$
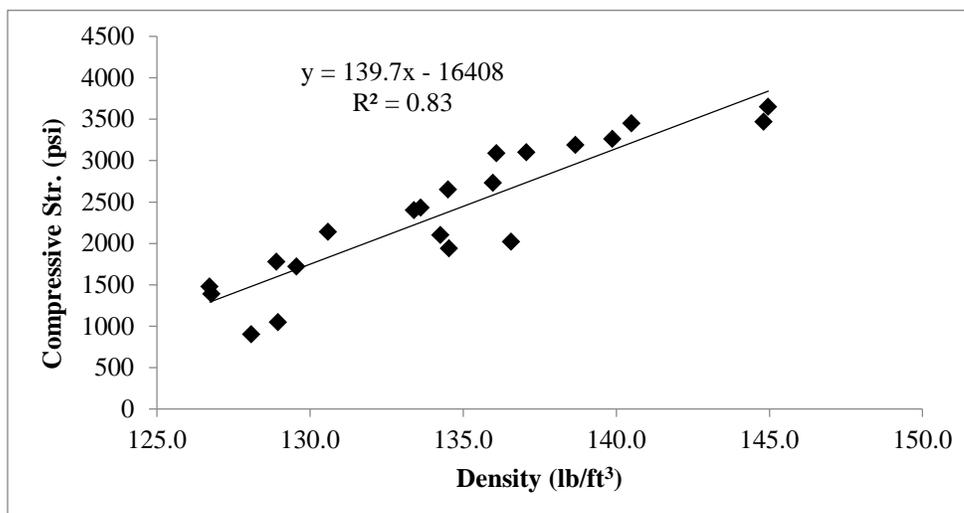
Figure 7. Compressive Strength (psi) As a Function of Density (lb/ft^3)

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For the selected air void range of 15% to 25%, densities of laboratory specimens indicated a range of 128.4 to 141.6 lb/ft^3 from the best fit line when tested in accordance with ASTM C1688 using Virginia materials. ACI Publication 522 (ACI, 2013) had lower densities for the PC ranging from 105 to 120 lb/ft^3, indicating that density depends on the level of compaction and materials being used, especially the specific gravity of aggregate. For the special provision, a range of 125 to 140 lb/ft^3 was selected based on the laboratory study using materials from Virginia projects along with the standard compaction effort. Figure 7 shows that the target strength for the mid-range of these densities is about 2,000 psi, which was also included in the special provision as the minimum value to ensure satisfactory performance.

The compressive strength was also correlated with cement content, as shown in Figure 8; the correlation coefficient was poor, indicating the high variability.

Splitting tensile strength results as they relate to hardened density are given in Figure 9. With increasing density, splitting tensile strength did increase with a correlation coefficient of 0.83. There were relatively few specimens examined for this test, so further testing is required in order for firmer conclusions to be drawn.
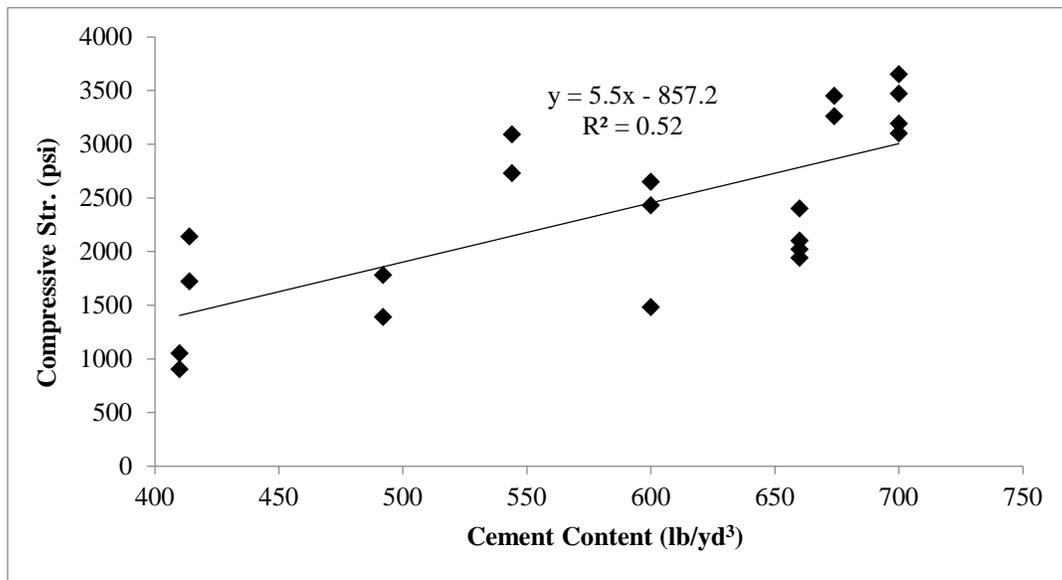

**Figure 8. Compressive Strength (psi) As a Function of Cement Content (lb/yd^3)**
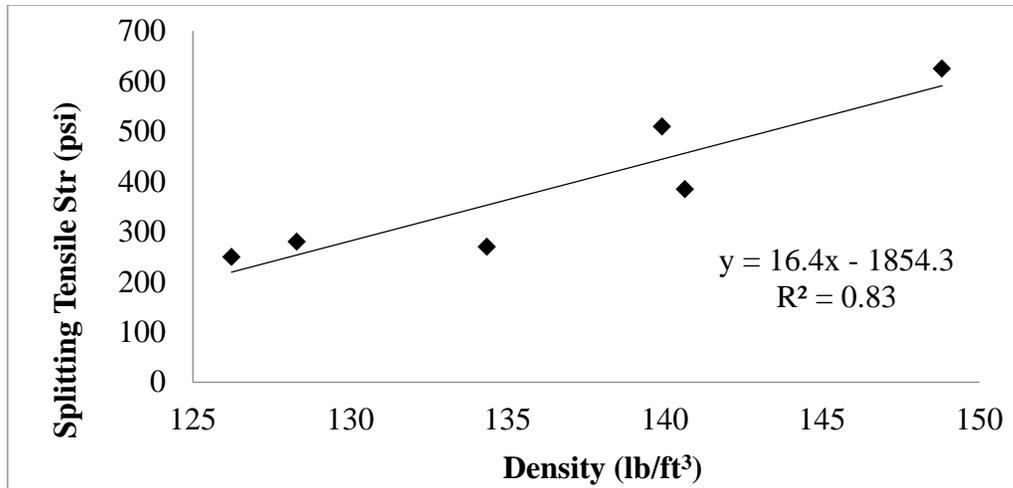
Figure 9. Splitting Tensile Strength (psi) As a Function of Density (lb/ft^3)

Impact and Abrasion Resistance

The intrinsically high void content of PC lends itself to concerns over its durability and its resistance to traffic loads. It was found, in accordance with ASTM C1747, that higher mass loss is associated with lower densities and higher void contents, as shown in Figure 10.
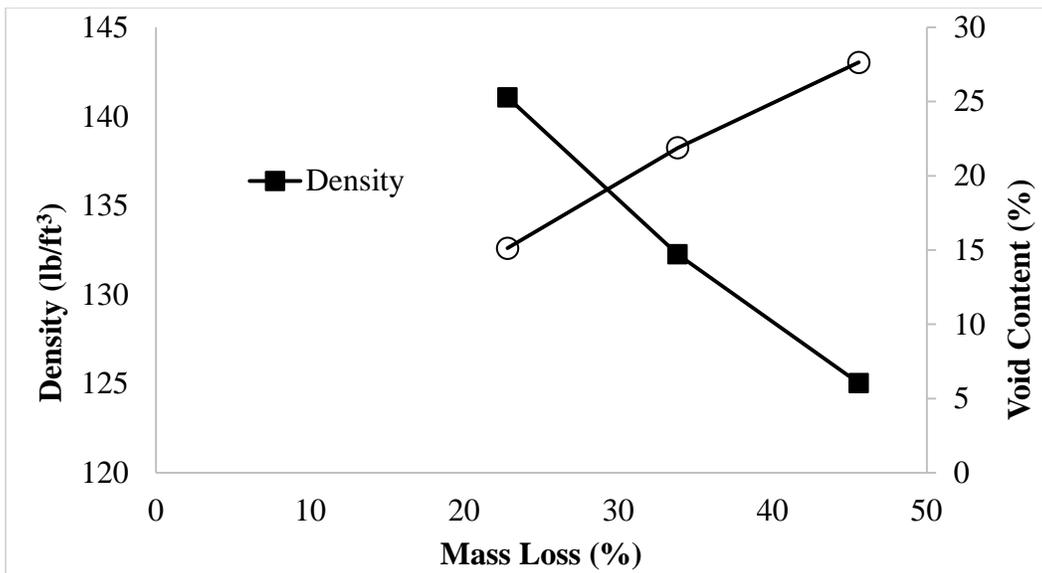

Figure 10. Density (lb/ft^3) and Void Content (%) As a Function of Mass Loss (%)

Hydraulic Conductivity and Recovery After Clogging

The infiltration capabilities of PC are expressed well through tests on hydraulic conductivity (ASTM D5084). It was found that the hydraulic conductivity is a function of void content according to an exponential line of best fit. Figure 11 shows the results of the hydraulic conductivity testing using clean water initially. The sequential tests analyzed how well the infiltration capabilities recovered after a clogging was introduced to the specimens.
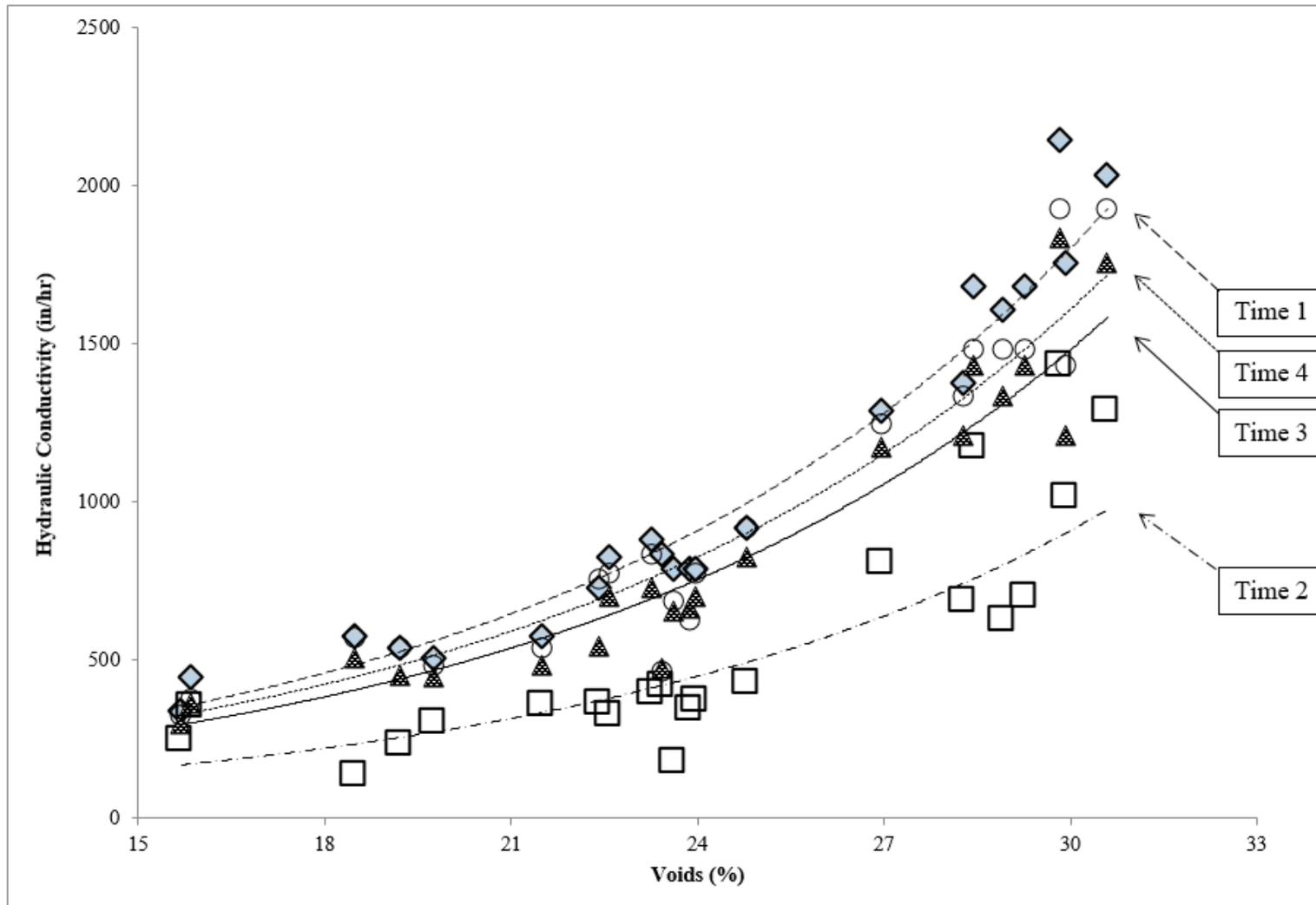
Figure 11. Hydraulic Conductivity (k) (in/hr) As a Function of Void Content (%): (1) Gray Diamonds: k Prior to Clogging Solution; (2) Squares: k After the Solution Containing Sand and Clay; (3) Triangles: k After One Vacuuming; (4) Circles: k After Both Pressure Washing and Vacuuming

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As explained in the section "Recovery After Clogging," the hydraulic conductivity was recorded 4 times and is shown in Figure 11 as Time 1, Time 2, Time 3, and Time 4. After the clogging solution passed through the specimens, the hydraulic conductivity was dramatically decreased. However, after the sequential cleanings, the hydraulic conductivity nearly reached the starting values.

Table 8 presents the exponential lines of best fit for the clogging recovery experiments. Figure 11 indicates a relatively high variability in the hydraulic conductivity results "after clogging solution." This variability is reflected in the relatively low correlation of the exponential line of Time 2 compared to the other experiments. This exponential relationship was demonstrated by Montes and Haselbach (2006).

Table 8. Exponential Lines of Best Fit for Clogging Recovery of Hydraulic Conductivity

State	Best fit line	R^2
1. Initial	$y = 59 * e^{0.11x}$	0.96
2. After clogging solution	$y = 27 * e^{0.12x}$	0.70
3. Vacuumed	$y = 51 * e^{0.11x}$	0.92
4. Pressure washed, vacuumed again	$y = 57 * e^{0.11x}$	0.90

CONCLUSIONS

- *Density is related to compaction effort and affects the infiltration rate and hydraulic conductivity. Lower density corresponds with higher infiltration rates and hydraulic conductivity providing improved drainage.*

- *Cement content and void content are related such that greater amounts of cement correlate with lower void content and reduced drainage.*

- *Density is related to compressive and flexural strength such that higher density is correlated with higher strength.*

- *Density is related to impact and abrasion resistance such that higher density is correlated with greater resistance to degradation.*

- *Optimization of infiltration capability and strength or abrasion resistance is essential for the production of PC with satisfactory performance.*

- *PC can recover its infiltration capabilities (via vacuuming and power washing) if clogged by sand and clay.*

- *The literature review showed that PC is a valid option for stormwater management in Virginia if it is installed and cared for properly.*

RECOMMENDATIONS

1. *VDOT's Materials Division should begin using the Special Provision for Pervious Concrete for Parking Lots developed in this study and provided in the Appendix as an option when permeable pavements are determined to be the proper stormwater best management practice for the parking lot in question.*

BENEFITS AND IMPLEMENTATION

Benefits

The benefits of implementing Recommendation 1 were realized when VDOT used PC in the Salem Park and Ride project in accordance with the special provision developed in this study. The selection of PC led to optimum use of the limited area for increased parking spaces without the need for a common retention pond that would have occupied a large area.

Implementation

The special provision developed in this study was used by VDOT with some modifications in the Salem Park and Ride project. Plans are underway to use the special provision with further modifications for the parking lot at VDOT's Shipman Area Headquarters.

ACKNOWLEDGMENTS

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APPENDIX

SPECIAL PROVISION

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
PERVIOUS CONCRETE FOR PARKING LOTS

August 9, 2016

I. **DESCRIPTION**

This work shall consist of furnishing and constructing pervious concrete in accordance with Sections 217 and 316 of the Specifications and this Special Provision. Pervious concrete is mainly used as pavement in low-volume traffic areas such as parking lots where storm water runoff is a concern.

II. **PERVIOUS CONCRETE MATERIALS, MATERIAL PROPERTIES AND PROPORTIONS**

1. **Cementitious material:** Cementitious material content shall be between 500 and 600 lb/yd^3. Type I or Type I/II cement alone or in combination with supplementary cementitious material can be used.

2. **Water:** Water shall be added such that the cement paste displays a wet metallic sheen without causing the paste to flow from the aggregate. Paste flowing would seal the voids at the bottom reducing the infiltration rate and also lead to poor bonding and lower strength at the upper surface.

3. **Coarse Aggregate:** Nominal maximum aggregate size shall be 3/8 inch.

4. **Fine Aggregate:** Fine aggregate up to 5% by weight may be used if approved by the Engineer to improve the strength and the durability of the concrete provided that the percent voids and the infiltration rate are maintained.

5. **Admixtures:** Air entraining admixtures shall be used to resist degradation from freeze-thaw cycles. Water-reducing admixtures may be used to decrease water content. Hydration stabilizers may be used to ensure workability for at least for one hour from batching time. Viscosity modifying admixtures may be used to maintain cohesiveness. Air entrainment shall be added at 1 oz/cwt.

6. **Fibers**: Polypropylene fibers complying with ASTM C1116 may be used to improve the strength and freeze-thaw durability of the pavement. Fibers shall be from approved list 35.

7. **Voids**: The mix design shall have a target void content of 20%. Voids in the fresh concrete may be between 15% and 25% when tested in accordance with ASTM C1688.

8. **Infiltration Rate**: The infiltration rate shall be greater than 100 in/hr when tested in accordance with ASTM C1701.

9. **Water-cementitious Materials Ratio**: w/cm shall be between 0.27 and 0.35.

10. **Density:** Fresh concrete density shall be between 125 to 140 lb/ft^3 when tested in accordance with ASTM C1688.

III. WEATHER RESTRICTIONS

Placement shall be permitted only when the ambient air and surface temperatures are 40°F or above. The maximum temperature for the concrete shall be 85°F. Extra precautions, such as immediate covering of the concrete or immediate fog misting, shall be taken when the air temperature exceeds 90°F.

IV. PRE-PLACEMENT CONFERENCE

Prior to placement, a pre-placement conference shall be held, and will be attended by the general contractor, pervious concrete contractor, concrete supplier, field testing agency, and the Engineer. In this conference, materials, personnel qualifications, concrete production, preparation, placing, curing, and testing procedures will be discussed. The Contractor shall submit a pervious concrete placement plan and detailed sequence of operations to the Department at least 21 days in advance of the pre-placement conference. The plan shall include the order of operations, types of equipment, curing procedures and durations, form types and process, and discussion of other items necessary to complete the work. Before work proceeds, the Engineer's approval shall be obtained for any issues that deviate from this special provision. The Department shall be notified of the date, time and location of the pre-placement conference at least 10 days prior to the meeting.

V. PERVIOUS CONCRETE PAVEMENT CONSTRUCTION

1. **Thickness:** The concrete shall be between 6.0 and 10.0 inches placed in a single lift unless otherwise stated in the Contract or directed by the Engineer.

2. **Forms:** Forms made of steel, wood, or other rigid material are permitted. Forms shall be free of debris, loose rust, and any adhering material.

3. **Subgrade Preparation:** Subgrade shall be leveled without any compaction to a uniform condition. Remove any deleterious material such as rocks, vegetation, or stumps. Construction traffic shall not be permitted to disturb the subgrade.

4. **Subbase:** Subbase shall be prepared such that reservoir stone layers are placed and compacted with a minimum of four passes of a heavy roller (10 ton min.) to ensure that particles are interlocked and stable. Construction traffic shall not be permitted to disturb the subgrade.

5. **Formwork:** Formwork, if used, shall be set, aligned, and braced so that elevation is within $\pm$ 3/4 inches of the Contract requirements. The thickness of pervious concrete shall be within (+1-1/2 inches, -3/8 inches) of the design thickness. If formwork is used, a form-release agent shall be applied to the formwork immediately before placement of the pervious concrete. The vertical face of previously placed concrete may be used as a form without the application of the release agent.

6. **Batching, Mixing, and Delivery:** Batching and mixing shall be in accordance with the ASTM C94. Concrete shall be placed within 60 minutes of the introduction of mixture water or aggregate to the cement. Use of hydration stabilizing admixture may allow longer time for the placement if approved by the Engineer. Additional water that is within the total water content of the mixture may be added on site. Fresh density must be met after the addition of water.

7. **Placing and Finishing:** The base shall be in a moist condition without any standing water prior to the placement of the concrete. Dry bases will absorb water from the pervious concrete resulting in reduced strength and quality. Concrete shall not be placed on frozen subgrade or subbase. Concrete shall be deposited and spread without segregation. A paving machine may be used. The concrete shall be compacted with a vibrating roller screed that spans the width of the section placed and exerts a minimum vertical pressure of 10 psi. The roller screed shall strike off the concrete deposited to between 1/2 and 3/4 inches above the final elevation. Cross rolling shall be performed to smooth the surface. The Contractor shall avoid overworking as it would close voids and seal the surface. The finished surface of the pavement shall be dense and open-textured as in the test panel (see Section VI, paragraph 3D herein).

8. **Jointing:** Joints shall be constructed at the locations shown in the Plans. Joint spacing shall not exceed 15 feet in any direction and joint depth shall be at least 1/4 of the pavement thickness. Slab length shall not exceed 1.5 times the slab width. Joints can be tooled-in in the fresh state or saw-cut in the hardened state. A roller with a beveled fin protruding at least 1/4 of the pavement thickness around the circumference shall be used to tool the joints in the fresh state. The sawing of joints should be done with care without spreading the dust and slurry into the pavement and avoid raveling of aggregates. Curing material shall be removed temporarily during jointing such that drying of the surface does not occur. Fog misting shall be applied if drying is occurring. Edging to a radius not less than 1/4 inches along isolation and construction joints shall be performed to reduce the raveling potential under traffic.

9. **Curing:** The pavement shall be cured using either polyethylene sheeting and wet burlap or polyethylene sheeting alone with a minimum thickness of 6 mils to retain the moisture within the concrete. Curing shall begin within 20 minutes of concrete discharge. If the evaporation rate exceeds 0.10 pound per square foot per hour pervious concrete shall not be placed. Fogging shall be applied if high evaporation rate greater than 0.05 pound per square foot per hour occurs. Evaporation retardants may be applied to minimize moisture loss from the surface. If evaporation retardants are used, once applied, there shall be no disturbance of the surface. The pavement and the edges shall be covered with the polyethylene sheeting. Polyethylene sheeting shall be secured so that wind cannot blow under or remove the sheeting. The concrete pavement shall be cured for seven days during which the concrete temperature is above 50°F. Any day that the temperature falls below 50°F extends the curing period one day.

10. **Maintenance:** The Contractor shall take care not to clog the pervious concrete with sand, dirt, and other debris during construction. The Contractor shall be responsible to repair clogged pervious concrete at his expense.

VI. **QUALITY CONTROL**

1. **Contractor:** Contractor shall have a National Ready Mixed Concrete Association (NRMCA) certified Pervious Concrete Craftsman or Pervious Concrete Installer on site during the pervious concrete installation.

2. **Mix Design Approval:** Contractor shall submit the mix design showing the ingredients, proportions, and the results on fresh density and void content (fresh ASTM C1688) to the Engineer for approval at least thirty (30) days prior to trial batching and test panel construction.

3. **Trial batch and Test Panel:** Upon approval of the mix design, the Contractor shall prepare a test panel measuring at least 225 ft^2 with the width and thickness specified in the Contract at least 30 days prior to construction. The panel shall be placed, jointed, and cured as specified in the Contract using the same materials, equipment and personnel proposed for the Work. The panel will be tested by VDOT according to the following:

   A. Fresh density (ASTM C1688).

   B. Thickness (ASTM C174) after 7 days of curing using cores.

   C. Density and void content (ASTM C1754) using cores.

   D. Infiltration rate (ASTM C1701) of test panel will be determined in the hardened state.

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E. Compressive strength from cores (minimum 2,000 psi at 28 days) (ASTM C39). Cores shall be 4 inches in diameter.

4. **Testing:** During construction, testing of the pervious concrete at the fresh and hardened states will be conducted by VDOT for acceptance. At least 1 ft^3 of Concrete will be sampled in accordance with ASTM C172 to determine the density and void content in the fresh state. Hardened state density and thickness will be determined from 4-inch diameter cores.

5. **Frequency of Testing:** Three cores shall be taken randomly from the test panel and from each lot of 5,000 ft^2 or a day's production if less than 5,000 ft^2 in accordance with ASTM C42 at least 7 days, but no longer than 28 days, after placement. Cores are to be taken from random locations by the Contractor at the direction and under the supervision of VDOT. Core holes shall be filled with A3 concrete or an approved patching material by the Contractor.

VII. **ACCEPTANCE**

1. **Test Panel:** Test panel shall be accepted if the infiltration rate is greater than 100 inches per hour, the hardened density is within ± 5 lb/ft^3 of the approved mix design, the void content on cores is within 4% of mix design, the average length of the cores is within -3/8 to +1-1/2 inches of the design thickness of the pavement with no single core less than -3/4 inches of the design thickness and the average compressive strength at 28 days is greater than 2,000 psi. A test panel that does not meet the requirements shall be rejected and a new panel shall be installed. The test panel meeting the requirements can be left in place and may be accepted as a section of the pavement.

2. **Pavement:** Test panel shall be accepted if the infiltration rate is greater than 100 inches per hour, the hardened density is within ± 5 lb/ft^3 of the approved mix design, the void content on cores is within 4% of mix design, the average thickness of the cores is within -3/8 to +1-1/2 inches of the design thickness with no single core less than -3/4 in of the design thickness and the average compressive strength at 28 days is greater than 2,000 psi. If a lot of 5,000 ft^2 or a day's production does not meet the acceptance criteria for infiltration rate, hardened density, length of core, or compressive strength it will be subject to rejection, removal, and replacement at Contractor's expense.

VIII. **MEASUREMENT AND PAYMENT**

Pervious concrete shall be paid per square yard. Payment shall include all expenses including the trial batch, test panel, placement and curing of the concrete.

Pay Item	Pay Unit
Pervious Concrete	Square Yard