APPROVAL SHEET

This Thesis
is submitted in partial fulfillment of the requirements
for the degree of
Master of Science

Author Signature: ______________________

This Thesis has been read and approved by the examining committee:

Advisor: Celik Ozyildirim, Ph.D., P.E.

Committee Member: Teresa Culver, Ph.D., P.E.

Committee Member: James Smith, Ph.D., P.E.

Committee Member: ______________________

Committee Member: ______________________

Committee Member: ______________________

Accepted for the School of Engineering and Applied Science:

Craig H. Benson, School of Engineering and Applied Science

December 2016

Development of a VDOT Special Provision for Pervious Concrete in Stormwater Management

---

A Thesis

Presented to

the faculty of the School of Engineering and Applied Science

University of Virginia

---

in partial fulfillment
of the requirements for the degree

Master of Science

by

Gail Margaret Moruza

December 2016

Acknowledgements

This work would not have been possible without the funding and research facilities of the Virginia Department of Transportation (VDOT) and its research branch, the Virginia Transportation Research Council (VTRC). The opportunities for implementation provided by VDOT are greatly appreciated.

I would like to thank the following individuals for their contributions to the success of this research:

- Dr. Celik Ozyildirim (thesis co-advisor), whose indomitable enthusiasm for concrete technology guided this project to speedy success.
- Dr. Teresa Culver (thesis co-advisor), for her invaluable input with regards to stormwater management.
- Dr. Jim Smith for his participation in my thesis committee and the feedback he provided throughout the process.
- Dr. Mike Fitch, Dr. Shabbir Hossain, and Roy Mills for their suggestions and feedback on research methodology.
- The VTRC lab technicians, Michael Burton, Kenneth Herrick, M-B Abdussalaam, and Sam Byers for their tireless assistance on field observations and laboratory analyses.
- The faculty and staff of the Department of Engineering at James Madison University for their tireless teaching and mentorship during my undergraduate years and for inspiring me to continually strive for excellence in my work.
- My loving fiancé, family, and friends who were there for me when the rubber really hit the road. You all are cherished beyond words.

Abstract

Stormwater runoff is a major concern as more land is developed into urban settings, morphing areas previously capable of infiltrating a large amount of water into impervious surfaces on which contaminants are collected and large volumes of runoff flow. Many effective practices for managing stormwater runoff exist currently with each method dependent on the surrounding development and the demands of that specific application. One treatment method available now is pervious concrete (PC), a type of permeable pavement that allows runoff to infiltrate, thus capturing contaminants before they reach the groundwater and slowing the runoff to alleviate flooding. Virginia Department of Transportation (VDOT) currently has no applications of pervious concrete. The purpose of this study was to conduct a literature review, field observations, and laboratory work to formulate a special provision by which VDOT could implement the technology of pervious concrete as a stormwater management tool. The results of the literature review, field observations, and laboratory work are presented in addition to the special provision formulated specifically for VDOT. From the work conducted in this study, it is evident that PC is a candidate for stormwater management that could perform satisfactorily in the Virginia climate and could be constructed with locally available materials.

Keywords: *pervious concrete, pavement, stormwater management, infiltration, density, void content, durability, hydraulic conductivity*

Table of Contents

Acknowledgements ii
Abstract iii
Table of Contents iv
List of Figures vi
List of Tables vii
Glossary of Acronyms 8
1.0 - Introduction 9
  1.1 - Stormwater 9
  1.2 - Best Management Practices 10
  1.3 - Pervious Concrete in Virginia 11
  1.4 - Special Provision 11
2.0 - Literature Review 13
  2.1 - History of Stormwater Management in the US and Virginia 13
  2.2 - Local Virginia Programs 18
  2.3 - Best Management Practices 19
  2.4 - Pervious Concrete 23
  2.5 - Mix Design 25
  2.6 - Pavement Design 27
  2.7 - Placement Procedures 28
  2.8 - Hydraulic Capabilities 29
    2.8.1 - Hydraulic Conductivity 29
    2.8.2 - Reduction of Runoff (Quantitative) 30
    2.8.3 - Interactions with Groundwater 31
  2.9 - Quality Assurance 31
    2.9.1 - Density 32
    2.9.2 - Strength 33
    2.9.3 - Freeze-thaw 34
    2.9.4 - Abrasion 34
    2.9.5 - Infiltration Rate 35
    2.9.6 - Clogging and Maintenance 35
    2.9.7 - Test Panel 36
3.0 - Purpose and Scope 37
4.0 - Methods 39
  4.1 - Field Placements 39
    4.1.1 – Stringfellow Park and Ride 41
    4.1.2 - Reston Parking Lot 44
  4.2 - VTRC Lab Work 46
    4.2.1 - Infiltration Rate 47
    4.2.2 - Mix Designs 48
    4.2.3 - Fresh Density and Void Content 51
    4.2.4 - Hardened Density and Void Content 52
    4.2.5 - Compressive Strength 54
    4.2.6 - Splitting Tensile Strength 55
    4.2.7 - Impact and Abrasion Resistance 56

    4.2.8 - Hydraulic Conductivity 57
    4.2.9 - Recovery after Clogging 58
5.0 - Results 60
  5.1 - Field Placements 60
  5.2 - VTRC Lab Work 63
    5.2.1 - Infiltration Rate 63
    5.2.2 - Mix Designs 64
    5.2.3 – Density and Void Content 69
    5.2.4 - Strength 70
    5.2.5 - Impact and Abrasion Resistance 72
    5.2.6 - Hydraulic Conductivity 73
6.0 - Discussion 67
  6.1 - Field Sites 67
  6.2 - VTRC Lab Work 68
7.0 - Special Provision 71
8.0 – Conclusions 72
9.0 – Recommendations and Future Work 74
10.0 - References 75
Appendix 79
  A.1 Special Provision 79

List of Figures

Figure 1: Stringfellow Park and Ride checkup 44

Figure 2: Reston Specimens 45

Figure 3: ASTM C1701 on lab specimen 47

Figure 4: ASTM C1701 on in-place concrete 48

Figure 5: Fresh concrete density test 51

Figure 6: Hardened concrete density specimen 53

Figure 7: Compressive strength testing 54

Figure 8: Splitting tensile strength 55

Figure 9: Abrasion test specimens 56

Figure 10: Falling head permeameter 57

Figure 11: Falling head permeameter with clogging solution 58

Figure 12: Infiltration rate and void content 64

Figure 13: Voids and cementitious content 68

Figure 14: Design density and measured density 69

Figure 15: Compressive strength and cement content 70

Figure 16: Density and compressive strength 71

Figure 17: Density and splitting tensile strength 72

Figure 18: Abrasion and Impact Resistance results 73

Figure 19: Changing hydraulic conductivity values with respect to treatment and void content 75

List of Tables

Table 1: Samples of Virginia storm data from Hershfield 17

Table 2: Examples of non-proprietary BMPs used in VA (VWRRC 2016b) 21

Table 3: Proprietary BMPs (VWRRC 2016d) 22

Table 4: Test Methods for Pervious Concrete Properties 37

Table 5: Mixture Proportions for the Fairfax Projects 40

Table 6: Laboratory batches immediately after Stringfellow 50

Table 7: Specimens from the Stringfellow project 61

Table 8: Specimens from the Reston Project 62

Table 9: VTRC Lab Mixes 66

Table 10: Regression analysis results 68

Table 11: Best fit lines for hydraulic conductivity values 66

Glossary of Acronyms

- ACI – American Concrete Institute
- ASTM – American Society for Testing and Materials
- BMP – Best management practice
- EPA – Environmental Protection Agency (US)
- IP – Interlocking pavers
- LID – Low impact development
- MS4 – Municipal separate storm sewer system
- NPDES – National Pollutant Discharge Elimination System
- NRCS – National Resource Conservation Service
- NRMCA – National Ready Mixed Concrete Association
- PC – pervious concrete
- PCA – Portland Cement Association
- SCM – Supplementary cementitious material
- SP – Special provision (VDOT)
- SWR – stormwater runoff
- TMDL – Total maximum daily load
- VA - Virginia
- VADEQ – Virginia Department of Environmental Quality
- VBH – Volume based hydrology
- VDOT – Virginia Department of Transportation
- VESCL - Virginia Erosion and Sediment Control Law
- VSMA – Virginia Stormwater Management Act
- VSMP - Virginia Stormwater Management Program
- VTRC – Virginia Transportation Research Council

1.0 - Introduction

1.1 - Stormwater

Stormwater runoff (SWR) is rainwater and snowmelt that flows over surfaces such as roads, roofs, or lawns (EPA 2016). Examples of areas in which SWR is a particular concern are agricultural areas, mining operations, and urban and suburban areas (US DOC 2016). Urban SWR is most prevalent in highly developed areas with high proportions of impervious surfaces such as parking lots, roads, roofs, and sidewalks, from which the stormwater flows, carrying with it contaminants and debris (EPA 2016). Ultimately, unmanaged SWR poses a threat to natural waterways, such as rivers, lakes, and coastal waters, through the introduction of pollution to natural waterways and through unnaturally high volumes of water (EPA 2016; US DOC 2016). The contaminants which SWR carries threaten the stability of freshwater as a natural resource which in turn has adverse economic affects through the loss of aquatic habitats on which industries and recreational activities depend (US DOC 2016; EPA 2016). High volumes of SWR can overwhelm infrastructure and cause flooding damage, which incurs additional economic costs (Ahiablame, et al. 2012). High volumes of SWR have also been shown to cause stream bank erosion and concurrent ecosystem damage; in one study in Pennsylvania, the urban streams were found to erode to a width 3.8 times larger than rural streams (Winston, et al., 2016).

Historically, typical stormwater management involved removing excess water to prevent flooding and sending it to a central location such as a centralized stormwater management pond, piping system, curb inlet, roadside ditches, or gutters (Ahiablame, et al. 2012). However, with the introduction of low impact development (LID), a different technique for stormwater management, known as volume-based hydrology (VBH) has been introduced (Ahiablame, et al. 2012). The intention of VBH is to decrease the volume of stormwater runoff so as to limit the stresses placed on the centralized stormwater control measures in addition to the natural environment (Ahiablame, et al. 2012). In support of low impact development, the Virginia Department of Environmental Quality (VADEQ) has identified methods for managing SWR containing point source and nonpoint source pollution as well as for decreasing volume of runoff (VADEQ 2016a). Point source pollution, or pollution from one particular location such as construction activities or a factory, is moderated by the State Water Control Law and the Clean Water Act through the Virginia Pollutant Discharge Elimination System (VADEQ 2016a). Nonpoint source pollutants, such as sediment, nutrients, toxins, and pathogens, are not from one central location, but are picked up as SWR flows over surfaces such as roads, roofs, lawns, and farmland (VADEQ 2016b).

1.2 - Best Management Practices

Managing SWR at its source is one approach for minimizing its adverse effects and imitating the hydrological patterns of the site in its pre-developed conditions (VWRRC 2016a; VWRRC 2016b). Specifically, the list of Best Management Practices (BMPs) and specifications for SWR compiled by the VADEQ, many of which come from the United States Environmental Protection Agency (EPA), include non-proprietary and proprietary post-construction activities that have been identified as effective methods for managing SWR (VWRRC 2016a). In the non-proprietary category, (permeable) pervious pavement has been shown to be an effective method for decreasing runoff volume and also decreasing pollutants in the runoff (VWRRC 2016b). Permeable (pervious) pavement is considered to qualify as LID, and consequently VBH, as it provides a "decentralized micro-scale control" for stormwater runoff (Ahiablame, et al. 2012). In doing so, pervious pavements help to alleviate the stresses on our water treatment systems and natural waterways by reducing peak discharge, decreasing runoff volume, encouraging infiltration, allowing groundwater recharge, and removing pollutants (Ahiablame, et al. 2012). The three most common types of permeable pavements used as stormwater control measures include interlocking pavers, porous asphalt, and pervious concrete (PC). Of these three types, analysis of PC indicates the highest permeability in conjunction with a mid-price range and longest service life, among other relative benefits (Maryland 2016).

1.3 - Pervious Concrete in Virginia

The Virginia Department of Transportation (VDOT) currently has no applications of pervious concrete though it has shown interest in pervious pavements for stormwater management. A special provision on porous asphalt was recently developed by VDOT that dictates the proper placement procedures and care for permeable pavement in VDOT owned and operated facilities, though it is not specifically for pervious concrete (VDOT 2015). Though VDOT has none for itself, there have been many applications of pervious concrete in the state of Virginia by private companies under the direction of the National Ready Mixed Concrete Association (NRMCA) and the American Concrete Institute (ACI) (NRMCA 2016; ACI 2013). Since pervious concrete performs best as a low-volume road, VDOT has many facilities such as rest areas, park and ride lots, secondary roads, shoulders, and slopes on the side of roads where pervious concrete could be used for stormwater management. VDOT is responsible for more than forty rest areas in the state of Virginia and, in 2013, the number of visitors at these rest areas per day ranged from 300 to 4,840 (VDOT 2013). In addition to the rest areas, Virginia has more than 300 Park & Ride lots, many of which are VDOT owned, that are viable options for implementing and studying the performance of pervious concrete pavement (VDOT 2016).

1.4 - Special Provision

To provide the opportunity for VDOT to implement pervious concrete as a stormwater management tool, a special provision is required and has been developed in this study that provides information on proper placement and care for pervious concrete. The guidance provided in the special provision is a culmination of a literature review, laboratory work using standard test methods, and analysis of two non-VDOT field applications of pervious concrete. The lab work that includes preparation of pervious concrete specimens and testing (using standard methods), and the field work, which is a case study of the Stringfellow Park and Ride and the Reston District Police Station parking lot (owned by Fairfax County) are presented in this document along with the literature review.

2.0 - Literature Review

2.1 - History of Stormwater Management in the US and Virginia

In the 1930s, the United States experienced the Dust Bowl, a time of intense dust storms as a result of poor farming practices as well as severe drought which displaced tens of thousands of people (VADEQ 2016c). In 1948, following the Dust Bowl, the United States federal government took its first steps in protecting the nation's water by implementing the Federal Water Pollution Control Act. The Great Depression had awoken a realization of the need to maintain the health and quality of soils as well as water. Almost thirty years later, in 1972, the Clean Water Act (CWA) was introduced as an amendment to the Federal Water Pollution Control Act, which gave control of water pollution policy in the United States to the Environmental Protection Agency (EPA) and also created the National Pollutant Discharge Elimination System (NPDES) Permit Program. The purpose of the EPA, founded in 1970, was to implement water pollution policy. An important tool to address water pollution is the NPDES Permit Program, administered by the EPA, which serves to control pollution from point source polluters. In addition to endeavors to maintain water quality on the federal levels, the states also began to implement their own laws following the Dust Bowl (VADEQ 2016c).

In 1938, The Virginia Soil and Conservation District Law, which created the Soil and Water Conservation Districts, was passed. These districts began the movement to ensure soil and water conservation was being maintained through local measures rather than the relatively distant federal government. However, not until the 1970s did Virginia become aware of the extent of erosion and sedimentation and the urgency with which it needed to be addressed. So, the Virginia Erosion and Sediment Control Law (VESCL) was passed in 1973 which ensured that soil erosion, sediment deposition, and nonagricultural runoff from regulated land-disturbing activities was controlled through statewide actions. Then, in 2012, the VESCL programs were combined with local municipal separate storm sewer systems (MS4) as well as the Virginia Stormwater Management Program (VSMP) for more effective and unified enforcement of regulations. The next year, the Virginia Department of Environmental Quality's (VADEQ) State Water Control Board took over management of the VESCL programs (VADEQ 2016c).

A major concern of the VSMP is managing both water quality and water quantity challenges that result from stormwater runoff (VWRRC 2016c). Specifically, nonpoint source pollutants such as automobile fluids or lawn care chemicals are deposited on surfaces such as roads, parking lots, and lawns where they may be swept away by the first flush of stormwater runoff (VWRRC 2016c). These pollutants are then channeled to areas where they can mix with drinking water supplies, waterways used for recreational activities, or natural ecosystems where they cause damage to the local organisms (VWRRC 2016c). If this contaminated water is allowed to percolate into the ground where there is highly permeable rock or insufficient soil coverage for natural filtration, groundwater contamination risk is fairly high (VWRRC 2016c). However, given sufficient soil depth, filtration of the contaminants from runoff is possible (VWRRC 2016c). Water quality is of particular concern in areas where pavements and roofs have replaced ground cover such as meadows and forests (VWRRC 2016c). Because the runoff is unable to percolate into the ground, it accumulates on the surface and then overwhelms the infrastructure or natural streams causing downstream damage and flooding. For example, a city block composed of the typical amount of roads, roofs, and sidewalks will produce nine times the volume of runoff than a wooded area of the same size (VWRRC 2016c).

As of July 1, 2014, the Virginia Stormwater Management Act (VSMA) dictates erosion and sediment control. In regions where an MS4 is present, a specific VSMP must be implemented. In regions with no MS4, either a VSMP can be voluntarily used or the VADEQ will implement the control measures (VADEQ 2016c). The VSMA includes the management of land developments of certain sizes; if the area is 1 acre or larger, if it is a portion of a developing area that is 1 acre or larger, if the local authorities have deemed it to be monitored by the VSMA, or if the area is 2,500 ft^2 or larger in the Chesapeake Bay Preservation Areas, then the measures set out by the VSMA apply. However, for areas between 10,000 ft^2 and 1 acre, the development is subject to the Virginia Erosion and Sediment Control Program authority and not the VSMA (VADEQ 2016c). Several categories of management options have been made available through the VSMP by the VADEQ for stormwater management in Virginia, most of which are minimum control measures specifically for MS4 programs (EPA 2005).

The BMPs provided by the VADEQ are designed with Virginia in mind. Historic records of rainfall data allow planners and developers to predict how much rain to expect for a given storm in a specific geographic region. In his 1961 paper on rainfall patterns in the United States, David Hershfield presented a series of isopluvial maps detailing rainfall amounts and frequency in which those amounts occur across the country (Hershfield 1961). Hershfield built his maps based on storms lasting from 30 minutes to 24 hours with return periods of 1 to 100 years (Hershfield 1961). The duration of a storm indicates how long the precipitation lasted while the frequency is the statistical likelihood of a storm of that intensity occurring. For example, a 100-year 30-minute storm will last for 30 minutes and its likelihood of occurring in a given year is 1/100 or 1%. The isopluvial map presents rainfall patterns through lines of equal precipitation, much like an elevation contour map (Hershfield 1961). Table 1 gives examples of the rainfall data for the state of Virginia presented by Hershfield in his paper.

Table 1: Samples of Virginia storm data from Hershfield used for predicting rainfall depth of storms (Hershfield 1961)

Frequency (year)	Yearly recurrence likelihood (%)	Duration (hour)	Rainfall Depth (inches)
1	100	0.5	0.8 - 1
2	50	1	1.6 - 2
5	20	2	2 – 3
10	10	3	3 – 4
25	4	6	4 – 5
50	2	12	5 – 7
100	1	24	7- 9

On average, Richmond, Virginia gets no more than 5 inches of rain in an entire month as the current average rainfall during the wettest months of the year (July and August) in Virginia is 4.5 and 4.7 inches respectively (US Climate 2016). It is important to keep these values in mind when designing BMPs for infiltrating stormwater for a pavement; achieving the highest possible infiltration rate is not always necessary. The trade-off of infiltration capabilities with system durability must be accounted for in that it is not necessary to design a system capable of hundreds of inches of infiltration if the likelihood of that volume of water being present in the system is less than 1% (Hershfield 1961). Accordingly, in their 2013 Virginia Stormwater Management

Handbook, the DEQ standardized the design criteria for volume reduction to account for 90% of the rainfall events, or those of 1” depth, throughout Virginia (DEQ 2013b).

2.2 - Local Virginia Programs

Apart from the VSMP, local entities throughout the state are invested in maintaining the good quality and managing the quantity of stormwater runoff. For example, the Chesapeake Bay Preservation Act and Program, the Floodplain Management Program, the Dam Safety Act, the VA Water Protection and Wetlands Permit Programs, and the Total Maximum Daily Load Program are all implemented by local entities to keep VA waterways in good condition (VWRRC 2016c).

The Chesapeake Bay is located in the coastal region of Virginia and has been under specific care and regulations through the Chesapeake Bay Preservation Act Program to reduce the impact of pollution and other stormwater runoff concerns (VWRRC 2016c). This program requires that 84 jurisdictions, approximately 56% of the state, monitor their impact on the Bay in hopes of recovering the health of that ecosystem (VWRRC 2016c; USDA 2016). The Floodplain Management Program prohibits the presence of stormwater management impoundment structures, which provide containment basins to store runoff from the contributing watershed, within a 100-year floodplain that has been designated by the Federal Emergency Management Agency (VWRRC 2016c). However, in some cases, construction in a flood zone is unavoidable, so the structure then must conform to the National Flood Insurance Program and also the local floodplain ordinance (VWRRC 2016c). Another notable stormwater management program in Virginia is the VA Water Protection and Wetlands Permit Programs which prohibits stormwater management impoundment structures in tidal and nontidal wetlands as well as perennial streams (VWRRC 2016c). However, stormwater impoundment structures and facilities are permitted in tidal and nontidal wetlands if the necessary permission is granted from Virginia Marine Resources

Commission and the VADEQ (VWRRC 2016c). The rivers, lakes, and tidal waters of Virginia are monitored for more than 130 pollutants to ensure that the levels are not beyond healthy levels (VWRRC 2016c). In order to maintain healthy levels, the VADEQ has identified the total maximum daily load (TMDL) for some pollutants in particular areas of the state that can be released into the waterways and if a community or area has levels above the TMDL, actions are taken to restore the water quality (VWRRC 2016c).

2.3 - Best Management Practices

The post-construction BMPs suggested by the VSMA are split into non-proprietary and proprietary (manufactured) BMPs (VWRRC 2016b). The aim of the BMPs is to encourage low impact development (LID) practices which imitate pre-development hydrologic conditions of the site while reducing runoff leaving the area. Table 2 shows a number of effective post-construction non-proprietary BMPs, provided by VADEQ, used to limit runoff from a developed site. This list is not all-inclusive, though it does include a wide variety of methods for managing runoff. Each technique has a known removal effectiveness identified by the VADEQ which indicates percentage of total phosphorus removed through reduction of runoff and treatment of the water.

Table 2: Examples of non-proprietary BMPs used in VA for stormwater management to encourage low impact development (VWRRC 2016b)

Method Name	Technique
Rooftop disconnection	Spaces between rooftops are created for runoff to be intercepted, infiltrated, filtered, treated, or reused
Sheetflow to conservation area, vegetated filter	Vegetated areas that slow runoff and allow infiltration adjacent to impervious surfaces
Grass channel	Slow and filter runoff
Soil amendments	Increases soil porosity through the addition of compost
Vegetated roof	Vegetated area on roof that allows infiltration and evapotranspiration from plants
Rainwater harvesting	Rainfall is directed to a storage tank for later use
Permeable pavements	Pavements that allow infiltration, thus reducing or eliminating runoff at the source
Infiltration	Temporary methods for slowing and infiltrating runoff
Bioretention (urban)	Landscaped area for infiltrating and filtering runoff
Dry swale	Shallow bioretention area as a linear channel
Wet swale	Combination of a wetland and dry swale
Filtering practice	Use engineered filter media to treat runoff, returns water to storm drainage system
Constructed wetland	Shallow, vegetated area designed to imitate naturally occurring wetland
Wet pond	Permanent storage area for stormwater runoff
Extended detention pond	Temporarily ponds stormwater runoff for infiltration and reduction of peak discharge downstream

In addition to the non-proprietary BMPs presented in Table 2, there are a number of proprietary BMPs that have been examined by the VADEQ and found to satisfactorily manage stormwater runoff (VWRRC 2016d). A sampling of these proprietary technologies is presented in Table 3. The VSMP regulations require that the VADEQ approve of the use of proprietary technologies prior to installation (VWRRC 2016d). The technologies listed in Table 3 can be identified as either hydrodynamic manufactured devices or as filtering manufactured devices. The hydrodynamic manufactured devices have a 20 – 25% event mean concentration removal efficiency of total phosphorous while the filtering manufactured devices remove 40 – 50% (VWRRC 2016d).

Table 3: Proprietary BMPs for stormwater management to encourage low impact development (VWRRC 2016d)

Device Name	Manufacturer	Device type
Aqua-Swirl® Stormwater Treatment System	AquaShield™, Inc.	Hydrodynamic Manufactured Devices
BaySeparator™	Baysaver Technologies LLC	
Continuous Deflective Separator® (CDS)	Contech Engineered Solutions LLC	
Downstream Defender®	Hydro International	
Dual Vortex Separator (DVS)	Oldcastle Stormwater Solutions	
Aqua-Filter™ Stormwater Filtration System	AquaShield™, Inc.	Filtering Manufactured Devices
StormTech® Isolator Row™	StormTech - A Division of Advanced Drainage Systems, Inc	
Up-Flo Filter® with CPZ media	Hydro International	
The Stormwater Management StormFilter® with ZPG media	Contech Engineered Solutions LLC	
BayFilter™ Stormwater Cartridge System	Baysaver Technologies LLC	

Pervious concrete is not only a non-proprietary BMP, but it is also proprietary when available in pre-cast slab form. Percoa, LLC as well as Stormcrete ™ are suppliers in the United States (Percoa 2016; Stormcrete 2016). One benefit of pre-cast pervious concrete is that its permeability can be more predictable given that it is cast in a known and maintained environment (Stormcrete 2016). Also, it has the advantage of being easily replaced in case extreme clogging occurs. However, regular preventative maintenance is still required for pre-cast slabs just as it is for cast-in-place concrete (Stormcrete 2016).

The most frequently used BMPs are those that allow infiltration and encourage groundwater recharge such as bioretention and infiltration trenches (VWRRC 2016b). Each BMP has its own associated advantage that is most appropriate for specific applications. Specifically, permeable pavements are particularly relevant to the Virginia Department of Transportation (VDOT) as it is responsible for most of the roadways in the commonwealth (over 125,000 lane miles), and therefore a significant portion of the commonwealth's impervious surfaces which generate stormwater runoff (VAAA 2016). Permeable pavements have the advantage of maintaining the function of an impervious surface (such as a parking lot or low volume road) while allowing infiltration and significantly reducing stormwater runoff.

2.4 - Pervious Concrete

The major types of permeable pavements are permeable interlocking concrete pavement (block pavers), porous asphalt, and pervious concrete (WisDOT 2012). Fundamentally, permeable pavements are similar to other infiltration-based BMPs as they utilize the uncompacted subgrade soils to infiltrate the runoff so that the water can leave the pavement system (NJ DOT 2004). All three types of permeable pavements have comparable pollutant load removal of 85-95% for total suspended solids, 65-85% for total phosphorus, 80-85% total nitrogen, 30% for nitrates, and 98% for metals (WisDOT 2012). In 2013, the VADEQ published updated performance specifications for contaminant capture and runoff reduction by permeable pavements (VADEQ 2013a).

The VADEQ designates two levels of performance for permeable pavement; the less elaborate strategy is Level 1 Design and the more elaborate strategy is Level 2 Design (VADEQ 2013a). These rankings have been determined through analysis performed by the VADEQ itself and are the expected performance of any permeable pavement installation that follows their specifications. Level 1 and Level 2 both show a 25% reduction of total phosphorus event mean concentration by BMP treatment process and also total nitrogen event mean concentration reduction. But, the two levels have different capacities for annual runoff volume reduction, total phosphorus mass load removal, and total nitrogen mass load removal with Level 2 consistently removing about 30% more than Level 1. Nutrient mass load removal for the Level 2 design is computed through multiplying the percentage volume remaining after reduction by the percentage EMC remaining and then subtracting that value from one (VADEQ 2013a). The 2013 VADEQ draft specification also indicates the stormwater function of permeable pavements to protect channels and mitigate flooding, though those capacities are determined by the specific site design (such as storage area within the loose aggregates beneath the pavement) and also the application of the Virginia Runoff Reduction Method. The VADEQ specifications also provides structural and hydraulic design requirements, material specifications, directions on adapting designs for specific geologic formations and climates, installation instructions, maintenance, community and environmental concerns, and a sample construction and inspection checklist. The 2013 VADEQ draft specification also includes a direct comparison between pervious concrete (PC), porous asphalt, and the interlocking pavers (IP). Of the three options that the VADEQ presents, PC has the highest design infiltration rate (though it heavily depends on specific design), is tied with IP for service life, and is in the middle for the cost range.

Pervious concrete is applicable for stormwater management in low-volume areas such as residential roads, driveways, and sidewalks (Montes and Haselbach 2006). PC is also thought to be useful for reducing the heat island effect in urban areas through its relatively light coloring, and for dampening road noise (Montes and Haselbach 2006; Caltrans 2016). Though, because of its inherently porous structure, strength and abrasion resistance are consistently a concern with pervious concrete in that with higher infiltration rate comes the potential of lower durability (Dong et al. 2013). Therefore, it is important that the PC be used in areas for which it is best suited or the mixture is designed in such a way as to improve the strength and durability without compromising too much infiltration rate (Dong et al. 2013).

2.5 - Mix Design

The basic mix design for pervious concrete includes cementitious materials, coarse aggregate, water, and a small amount of (if any) fine aggregates (NRMCA 2004). The American Concrete Institute (ACI) has compiled a design reference for pervious concrete that indicates the necessary components of the mix (ACI Committee 522 2013). Typically, aggregates are uniformly graded at 3/8” size (Anderson, et al. 2013). The water-cementitious materials ratio is typically between 0.35 and 0.45, though some report 0.25 – 0.35 (NRMCA 2004; Putman and Neptune 2011). PC can, but is not required to, include chemical admixtures such as water reducing, air entraining, and viscosity modifying admixtures in addition to supplementary cementitious materials (SCM) such as fly ash, slag cement, and silica fume and polymer modifications, and fibers (Anderson, et al. 2013; Chen et al. 2013). The allowable supplementary cementitious materials, which are used to enhance the binder properties, are determined in accordance with ASTM C618, C989, and C1240 (ACI 2013; Chen et al. 2013). In Chen’s 2013 study, it was shown that strength of PC can be high and fatigue resistance can be improved with SCMs and polymer additions even while maintaining the needed infiltration rate (Chen et al. 2013).

Fine aggregates increase the strength and improve the freeze-thaw resistance, but also decrease the infiltration rate of the concrete as they fill in the pore space through which the water would otherwise travel (NRMCA 2004). Some investigations have been made into the performance of fibers in pervious concrete as a means for improving the strength and durability of PC mixtures in terms of tensile strength, better resistance to freeze-thaw degradation, resistance to abrasion and cracking, lowering the amount of edge curling, and decreasing the saw-cut joint frequency (Kevern, et al. 2015; Amde and Rogge 2013). However, there have been mixed results on the benefits of fibers in terms of tensile strength in pervious concrete as the benefits are dependent on complex relationships between quality of paste, fiber type, length, and fiber quantity in the PC (Thakre, et al. 2014). In order for the fibers to have a beneficial impact on the PC mix, there must be sufficient paste content to coat both the coarse aggregates and the fibers (Kevern, et al. 2015). Specifically, cellulose fibers as well as monofilament, micro-type polypropylene, and macrosynthetic fibers were analyzed by Kevern in his study on PC (Kevern, et al. 2015). Both the type of fiber and the fiber length impact the improvement of PC durability and continuation of infiltration rate (Kevern et al. 2015). For example, in the Kevern et al. (2015) study of macrosynthetic fibers, it was determined that mixes containing longer fibers (2.25 in) had better freeze-thaw durability while dosages of the shorter fibers (1.5 in) had to be increased to achieve similar results (Kevern et al. 2015). Additionally, their results showed that mixes with fibers had no change in compressive and tensile strengths while abrasion resistance was increased in comparison to mixes without fibers. However, in a Maryland study on PC, cellulose fibers did show an increase of tensile strengths and freeze-thaw durability (Amde and Rogge 2013). Overall, the fibers decreased infiltration rate of PC in the study by Kevern (Kevern, et al. 2015). However, it has been found that the inclusion of fibers can allow sufficient infiltration rates while increasing compressive strength (Dong et al. 2013; Amde and Rogge 2013).

Contrary to common practices for non-pervious concretes, neither slump nor air content values are measured because the readings are expected to be unreliable since those characteristics are dependent on compaction technique and other placement procedures (NRMCA 2004). Rather, the criterion for acceptance is void content (15 – 25%), as indicated by the concrete density, which is predetermined by the designer according to the site-specific stormwater requirements (NRMCA 2004).

2.6 - Pavement Design

Proper design of the whole pavement system is imperative for minimizing risks such as freeze-thaw degradation or clogging (NRMCA 2004). Even if the concrete itself is proportioned, mixed, and placed well, if the storage area beneath the pavement is not sufficient for the water input, the pavement will become saturated and when a freeze-thaw cycle occurs, the pavement will crack and degrade (NRMCA 2004). Though the VADEQ leaves it up to the designer of the specific project, the NRMCA recommends 8 – 24 inches beneath the concrete of open graded stone (NRMCA 2004; VADEQ 2013a). For permeable pavement in general, the VADEQ recommends two different pavement designs; Level 1 is for soil infiltration beneath the pavement that is less than 0.5 in/hr and therefore requires a drain in the pavement subbase while Level 2 requires more than 0.5in/hr to eliminate the underdrain requirement (VADEQ 2013a). In order for the soil to meet the 0.5 in/hr infiltration capabilities, the soil can have no more than 40% silt/clay and no more than 20% clay (VADEQ 2013a). The VADEQ allows the complete omission of testing the underlying soils if an underdrain is included in the design of the pavement system (VADEQ 2013a). Additionally, the VADEQ outlaws the construction of PC over fill soil as this subbase would provide poor support (VADEQ 2013a).

Furthermore, it is helpful to design the pavement in such a way as to limit the run-on from surrounding areas which likely carry clogging materials such as sediment or debris (Caltrans 2016). For example, strategic placement of a curb could prevent sediment from running onto the pavement (Caltrans 2016). Pavement thickness is determined by the predicted traffic load while the storage layer thickness is determined by the expected volume of runoff to be infiltrated as well as the infiltration capabilities of the underlying soils (Henderson and Tighe 2012). Pervious concrete pavements can be designed using virtually any standard concrete pavement procedure (Delatte 2007). However, there are two programs that directly relate to PC; these programs for the design of a pervious concrete pavement system are PerviousPave by American Concrete Paving Association (ACPA) and Porous Concrete Hydrological Design and Resource Software produced by the Portland Cement Association (PCA) (Henderson and Tighe 2012). ACPA's PerviousPave provides results optimized for both structural and stormwater-management requirements while the PCA program addresses the hydrological design only.

2.7 - Placement Procedures

Effective PC is a result of well-designed mixes and good construction practice (Henderson and Tighe 2012). The NRMCA is the national authority on the placement of pervious concrete with its Pervious Concrete Contractor Certification Program (NRMCA 2016). The NRMCA provides three certification levels; the most basic level is the Technician, followed by the Installer, and then the most advanced certification is the Craftsman (NRMCA 2016).

In order for the cement paste of the pervious concrete to hydrate properly and also for sufficient strength to be attained, proper and timely curing is essential (NRMCA 2004). The NRMCA recommends the 7-day curing process, using plastic sheets, to begin strictly within 20 minutes of placement, or else risk the surface of the concrete losing moisture (NRMCA 2004). Additionally, the NRMCA recommends jointing be accomplished with a rolling jointing tool and should be spaced in a manner similar to concrete slabs on grade (NRMCA 2004). If spaced too far, the pavement may form cracks as a result (Henderson and Tighe 2012). Fixed forms or slip-form pavers are permissible according to the NRMCA (NRMCA 2004).

As is evident with the NRMCA's interest in pervious concrete, ready-mixed concrete is available and commonly used (NRMCA 2016). However, other delivery methods of pervious concrete are available as well. For example, pre-cast pervious concrete slabs, which can be removed and replaced if damaged or not performing well, are convenient because of greater structural and performance quality assurance and increased uniformity of the product (The Concrete Producer 2015). Furthermore, in one study in particular by Hernderson and Tighe in 2012, PC prepared in a mobile mixer performed well (Henderson and Tighe 2012).

2.8 - Hydraulic Capabilities

2.8.1 - Hydraulic Conductivity

The hydraulic conductivity of a saturated medium, or how readily water flows through the pores of the medium, is a property dependent on porosity, conductance of the medium, tortuosity, and fluid density and is not equivalent to water velocity (Montes and Haselbach 2006; Anderson, et al. 2013; NRCS 2016). Darcy's Law uses hydraulic conductivity to predict fluid flow (Montes and Haselbach 2006). Laminar flow is a requirement for hydraulic conductivity measurements, and even though laminar flow cannot be assumed for all cases in PC, the falling and constant head permeameter lab tests are conducted in such a way as to slow the water velocity so that laminar flow is a safe assumption (Montes and Haselbach 2006; Qin et al. 2015). Montes and Haselbach (2006) found that the saturated hydraulic conductivity values of PC with porosity values in the range of 0.15 to 0.30 was $5.5\text{x}10^{-3}$ to $4.6\text{x}10^{-1}$ in/s (0.014 – 1.19 cm/s). Unsaturated hydraulic conductivity, however, is a hysteretic quality dependent on the degree of saturation of the medium, and must be determined as an approximation based on saturated conductivity or measured in a laboratory setting (Montes and Haselbach 2006). Since pervious concrete is intended for applications when saturation is highly likely to occur, unsaturated hydraulic conductivity is not a critical parameter for characterizing the performance of PC and therefore is not explored in this paper (Montes and Haselbach 2006).

Methods for modeling the flow of moisture through pervious concrete that relate porosity and hydraulic conductivity have been explored, though not in great depth. One risk of such a model is that porosity of PC is not the only determinant of infiltration rate because of the grain size distribution in addition to the fact that PC particles are consolidated and cemented together; not all pore spaces in PC are connected and some lead to dead-ends where fluid gets trapped (Montes and Haselbach 2006). The Ergun equation has been applied to flow through pervious concrete because it incorporates many different flow regimes into its modeling of flow through packed beds (Montes and Haselbach 2006). However, the Ergun equation typically underestimates flow through PC because of the inaccuracy in particle sizes as well as the distribution of cement material (Montes and Haselbach 2006). In 2006, Montes and Haselbach published a study wherein the Carman-Kozeny equation was applied for modeling hydraulic conductivity with respect to porosity of pervious concrete (Montes and Haselbach 2006). It is a useful equation because it uses total porosity with material-specific alterations such as the specific surface area of the material (Montes and Haselbach 2006).

2.8.2 - Reduction of Runoff (Quantitative)

Once the water has passed through the pavement, it can be allowed to infiltrate into the underlying soils, be channeled out of the system to a treatment or holding facility, or released to a nearby waterway (Anderson, et al. 2013). To quantify how much reduction of runoff there is when PC is installed, some researchers have applied the Natural Resource Conservation Service (NRCS) curve number hydrology methods. Curve numbers are particularly helpful for comparing areas into which runoff is able to percolate against areas in which it is unable to percolate. The curve number of an area is an empirical number that helps estimate how much runoff is stored in a catchment, or otherwise how much is likely to leave the catchment (Schwartz 2010). In his 2010 paper, Schwartz suggested a method by which a site can be categorized that gives pervious concrete a design-specific curve number (Schwartz 2010).

2.8.3 - Interactions with Groundwater

There is evidence that, if allowed to percolate into the underlying soils, the water table underneath the pavement may be raised (Anderson, et al. 2013). However, if the water table becomes too close to the storage layer of the pervious concrete, it may cause a back-up in the pavement which could potentially damage the pavement as well as cause flooding in the vicinity (VADEQ 2013a). Furthermore, the VADEQ recommends avoiding construction of PC in locations that are known to recharge drinking water aquifers, especially if the soils in the subbase are particularly high in infiltration rate (VADEQ 2013a). If the PC is installed near a drinking water aquifer, there should be an impermeable liner and underdrains to channel the water to a treatment facility or another location away from the recharge area (VADEQ 2013a).

2.9 - Quality Assurance

In order for PC to perform at the standards needed and expected, several characteristics must be monitored and taken into account when designing both the mix design and the pavement structure itself. Specifically, the density, the strength of the material, its freeze-thaw durability, abrasion resistance, its tendency to clog, and the infiltration rate must be considered. Not only must these be considered, but several test procedures described by ASTM, ACI, and NRMCA should be followed to ensure the quality of the pervious concrete pavement system. Even with the preventative measures taken to create a high-quality product, PC can still clog; therefore, it has to be maintained to perform satisfactorily over its lifetime. It is essential to know how to care for the pavement in such a way as to regain the infiltration rate once a clogging material has been introduced to the system. Finally, a test panel must be installed which follows exactly the design that the actual pavement will follow in order to determine if the pavement design will be successful.

2.9.1 - Density

The density of PC can be measured while the concrete is in the fresh state as well as in the hardened state by applying ASTM C1688 and C1754, respectively. As the void content of a PC mixture increases, its density decreases accordingly, hence lower densities lead to lower strengths (Putman and Neptune 2011). A significant factor on the density of PC is the compaction method, the point of which is to eliminate large voids to strengthen the concrete without closing the voids needed for infiltration (Putman and Neptune 2011). Putman and Neptune explored different compaction methods in their 2011 study on the three methods of rodding, proctor hammer, and dropping (Putman and Neptune 2011). In their study, it was determined that rodding the samples resulted in more variable density values of the PC while the Proctor hammer and dropping were less variable. However, in a study done by the Maryland State Highway Administration, all of the samples were rodded and the results were found to be reliable and repeatable (Amde and Rogge 2013). In Putman and Neptune's study (2011), the samples consolidated with the proctor hammer were most similar to the actual pavements using the same mix design than the other compaction methods. When comparing cylinders to the pavement and slabs to the pavement, it was determined that the cylinders typically overestimated the pavement density while the slabs were more representative of reality (Putman and Neptune 2011). The cylinders were 0.5 ft in diameter and 1 ft in height and the slabs were 0.5 ft in thickness and either 1x1 ft, 1.5x1.5 ft, or 2x2 ft in length and width.

2.9.2 - Strength

In its 2014 report on Pervious Pavement Design Guidance, Caltrans identified only certain areas and contexts as suitable for pervious pavement because of its relatively low strength compared to conventional paving materials (Caltrans 2014). Specifically, the areas according to Caltrans which are considered "low risk" for pervious pavement failure are those which receive no vehicular loads, few heavy vehicular loads, or moderate numbers of heavy vehicular loads at low speeds; these include landscaped areas, sidewalks, bike paths, miscellaneous pavements accepting run-on from impervious surfaces, parking lots, park and ride lots, maintenance access roads and stations, scenic overview areas, and rest areas (Caltrans 2014). In general, compressive strength of pervious concrete is in the range of 400 to 4000 psi, though neither compressive strength nor flexural strength are properties used for acceptance criterion as they are so heavily dependent on factors such as compaction method, porosity, w/c ratio, aggregate to cement ratio, aggregate size/type, and admixtures (NRMCA 2004; Anderson, et al. 2013). However, strength is tested frequently and provides good information on uniformity and the performance of the pavement. The pores of PC have been shown to have a vertical distribution which is likely to heavily influence the results of any conventional strength tests (Chandrappa and Biligiri 2016). In fact, there is no standard test for determining the strength of pervious concrete, so the ASTM method for conventional concrete is typically used (Anderson, et al. 2013; Chandrappa and Biligiri 2016).

2.9.3 - Freeze-thaw

Most applications of PC have been in relatively warm, temperate climates where the concrete would not typically experience significant stress from freezing and thawing cycles (Anderson, et al. 2013). However, with the proper mix designs and maintenance, the risks of freeze-thaw deterioration can be diminished as damage from cycles of freezing and thawing is dependent on saturation of the PC (Anderson, et al. 2013). In fact, one study conducted on the freeze-thaw cycles of PC placements in Canada found that the pavement survived the cycles with no signs of distress (Henderson and Tighe 2012). A few methods have been developed and studied that indicate prevention of damage from freezing and thawing is possible. Fly ash, a supplementary cementitious material with a relatively small particle compared to cement, has been shown to improve resistance to freeze-thaw degradation at the same time as maintaining proper void ratios, hydraulic conductivity, and compressive strengths (Anderson, et al. 2013). Other methods for minimizing the impact from freezing and thawing cycles are the inclusion of air entrainment admixtures, latex, fibers, and fine aggregates (Henderson and Tighe 2012).

2.9.4 - Abrasion

Abrasion resistance of PC is important because it is indicative of the material's durability (Dong et al. 2013). In their 2013 analysis of different methods of determining PC abrasion resistance, Dong, et al. compared the Cantabro test (which is similar to ASTM C1747) to the loaded wheel abrasion test (ASTM C944). Commonly, abrasion and impact resistance of PC is measured using ASTM C1747, which determines the potential resistance to degradation by measuring the mass loss of specimens subjected to combined action of impact and abrasion in a rotating steel drum (Los Angeles machine) (Smith, et al. 2012). Dong, et al. (2013) determined that the Cantabro method was actually rather ineffective in determining abrasion resistance of PC as the specimens primarily underwent stresses from impacts, though it had good sensitivity and is repeatable. Dong et al. found lower variability with the rotary cutter test (ASTM C944), but Munoz, in his 2012 study on PC, found lower variability with the Los Angeles machine (ASTM C1747). ASTM has chosen to test the abrasion of pervious concrete using the Los Angeles machine (Munoz 2012).

2.9.5 - Infiltration Rate

The infiltration rate of in-place PC can be measured using ASTM C1701 which measures the time for water kept at a constant head to percolate through a 12" diameter ring into the concrete pavement (ASTM 2015a). Depending on its design and placement procedures, PC can infiltrate water at rates of 280 – 1400 in/hr which is far greater than any typical storm will deliver; most PC systems are designed to infiltrate run-on from surrounding areas as long as it does not carry sediment or other clogging materials with it (Haselbach, et al. 2006). After placement, the minimum infiltration rate specified in the state of Wisconsin is 100 in/hr (WI, 2014). In-service minimum infiltration rate is specified as 10 in/hr by Caltrans and also Wisconsin (Caltrans, 2014; WI, 2014).

2.9.6 - Clogging and Maintenance

Clogging of PC from soil, sand, or other debris, is one of the major ways by which PC loses its effectiveness as a stormwater management practice (Anderson et al. 2013). NRMCA provides a guide for PC pavement maintenance and operations that describes maintenance protocol in three levels as routine maintenance, periodic maintenance, and deep cleaning/unclogging (NRMCA 2015). Routine maintenance, recommended to be performed at least monthly, includes visual inspections, blowing off the surface with a leaf blow or similar device, truck-sweeper and/or dry vacuuming (NRMCA 2015). Periodic maintenance, which should be conducted during seasonal shifts, should remove any debris that could prevent proper drainage and cause freeze-thaw damage (NRMCA 2015). NRMCA suggests that properly conducted regular and periodic maintenance can help in preventing the need for renovation or rehabilitation. In the case that the system needs significant cleaning, simultaneous pressure washing and vacuuming should be conducted, for which specialized equipment exists. The guide cautions that high water pressures that can cause raveling should be avoided. According to the NRMCA, deep cleaning should be conducted when the infiltration rate falls below 100 in/hr.

Another form of maintenance is preventative maintenance which serves to prevent the introduction of clogging materials. For example, avoid as much leaf litter as possible on the pavement surface and also block sediment from running on to the pavement surface through raised sections (Hunt 2009). During construction, attention should be paid to avoid clogging the pervious pavement with construction debris or uncovered soil. Or, better yet, to place the pervious concrete towards the end of the construction activities.

2.9.7 - Test Panel

Test panels are recommended to determine if the mix design and the equipment and methods for placement are satisfactory. For example, ACI recommends implementing 2 test panels, each of at least 225 ft^2, at any location where PC is installed (ACI 2013). These test panels are to exactly match the mix proportions and installment procedures that are chosen for the actual PC pavement. If the test panel performs satisfactorily, construction can proceed with the actual pavement. However, if it is not satisfactory, ACI recommends the contractor to replace the test panel in such a way as to match the project requirements (ACI 2013).

3.0 - Purpose and Scope

The purpose of the project was to develop a special provision on the use of pervious concrete as a stormwater management tool for the Virginia Department of Transportation. This special provision was constructed through a literature review in addition to field and laboratory analyses. The literature review served the purpose of compiling the current knowledge and practices involved with pervious concrete. The laboratory work reflected the findings of the literature review in that it informed the test procedures performed. The purpose of the laboratory analyses was to determine the properties of pervious concrete for applications across Virginia with respect to various void contents (15% – 25%) and their corresponding mix designs and preparation methods. Material properties of the pervious concrete with various void contents were determined using the tests listed in Table 4.

Table 4: ASTM test methods for fresh and hardened pervious concrete properties

Property	**ASTM Method**
Freshly Mixed Concrete	
Density and void content	C1688 (ASTM 2014)
Hardened Concrete	
Density and void content	C1754 (ASTM 2015b)
Infiltration rate	C1701 (ASTM 2015a)
Impact and abrasion resistance	C1747 (ASTM 2015c)
Hydraulic conductivity	5084 (ASTM 2010)
Compressive strength	C39 (ASTM 2004)
Splitting tensile strength	C496 (ASTM 2011)

Furthermore, the behavior of pervious concrete under clogging conditions has been examined. After a clogging solution was introduced to the concrete, the specimens were cleaned with vacuuming and also power washing and vacuuming and the subsequent infiltration capabilities were examined. The special provision for the implementation of pervious concrete at certain VDOT facilities includes the test procedures necessary to validate the performance specifications. The special provision includes materials, pervious concrete mix design, fresh and hardened concrete test procedures, trial batching and testing, and construction quality assurance/control.

4.0 - Methods

In order to understand the behavior of PC, to identify the relevant testing procedures for characterizing pervious concrete (PC), and to develop a special provision on the use of PC as a stormwater management practice for Virginia Department of Transportation (VDOT), three components of the research were conducted. First, a comprehensive literature review was performed to gather information on the current knowledge of stormwater best management practices, specifically PC. This literature review was presented in the previous section of this report. It was evident that conflicting results were presented by different researchers in developing, testing, and maintaining PC. This study addressed some of these issues through field and laboratory investigations to develop an implementable special provision that would enable the application of PC in VDOT facilities. Next, field applications of PC in the state of VA performed by non-VDOT entities were observed at two locations in Fairfax County and the performance of in-place concrete and samples were analyzed. Based on what was discovered in the literature review and the analyses of the field placements, laboratory experiments were carried out in the lab space of the Virginia Transportation Research Council (VTRC) located in Charlottesville, VA.

The special provision developed for VDOT based on the literature review, field observations, and laboratory work is provided in the appendix of this report.

4.1 - Field Placements

As the project was initiated, two field projects became available for placement observation, sampling, and testing; these projects were a Park and Ride facility at Stringfellow, Fairfax, VA and the parking lot of Reston District Police Station also in Fairfax, VA. Both at these sites and in the VTRC lab using aggregates from the projects, specimens were prepared with varying void contents and tested to evaluate the properties of the pervious concrete.

Concrete at the two projects was furnished by ready-mixed concrete plants owned by the same company within a 20-minute drive of both sites. The concrete mix design for both projects is given in Table 5; the same ingredients from the same sources were used in both projects. Coarse aggregate was diabase traprock with a nominal maximum size of 3/8 in. The SSD (saturated surface dry) relative density (specific gravity) of the coarse aggregate was 2.98 while the dry rodded unit weight was 111 lb/ft^3.

Table 5: Mixture Proportions for the Fairfax Projects

Material	lb/yd^3
Portland cement	550
#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 concrete was delivered from the truck using a conveyor and was compacted by a vibrating roller pulled manually. It was also rolled crosswise by a non-vibrating roller and joints were formed in the fresh concrete using a bladed roller. The fresh pavement was covered with black polyethylene sheet for curing immediately so that the 20 minute delay time limit was met. The mix and placement procedures used at the Reston Police Department were the same as that used in the Stringfellow lot; the same PC contractor with NRMCA's highest certification level (Craftsman) worked both projects.

4.1.1 – Stringfellow Park and Ride

Design and Placement

For the Stringfellow Park and Ride facility, ACI 522.1-10 was used as a specification by the contractor for the placement procedures. The Stringfellow site includes an entrance roadway and a parking lot to serve the Park and Ride facility. The parking stalls consist of pervious concrete while the drive lanes consist of regular asphalt. The area of pervious concrete was 33,000 ft^2. Pervious concrete was specified to have a minimum thickness of 6 in, a minimum connected void space of 20%, and a joint spacing of 12 ft. Beneath the pervious concrete is a variable depth aggregate reservoir for stormwater storage during and between events. To enable continual assurance that the pavement is draining properly, there are several observation wells flush with pavement. As part of the site design, it is planned that the pervious concrete be cleaned on an annual basis to prevent materials such as grit, sand, and salt from clogging the voids. Within the aggregate storage layer is a perforated inflexible 6 in diameter pipe which is used to collect the drained runoff and direct it to an area where it is stored and allowed to infiltrate into the soil.

To prevent fine soil from traveling upward through the aggregate base where it can clog the system, the storage area under the pavement was encased with non-woven polypropylene geotextile filter fabric. The perforated inflexible underdrain pipe was installed within a 10 in-layer #57 aggregate, so that there was at least 2” of aggregate above and below the pipe to prevent damage during compaction. Above the #57 layer, #2 aggregate was placed in 4 - 8 in lifts and compacted with at least 4 passes of a 10-ton static roller. Above the compacted #2 aggregate, a choker course of 1 - 2 in of #8 aggregate was placed and compacted by at least 4 passes of the 10-ton static roller. All stone had to be washed and less than 1% could pass a #200 sieve.

Upon completion of the Stringfellow lot, infiltration rate testing was required to ensure that the pavement would suffice as a stormwater management practice. Testing the infiltration rate required 5 gallons per minute to be poured and infiltrated without puddles forming or surface runoff. Furthermore, the facility was to be inspected at 18 - 30 hours after a significant rainfall (0.5 – 1.0 in) or artificial flooding to ensure proper drainage. All landscaping and artificial grass was to be completed before the placement of the pervious concrete to prevent clogging materials such as mulch or soil to be introduced to the pavement.

Protection and Maintenance

During construction, it was required that the pervious concrete be protected from erosion and sediments from stormwater runoff so the contributing drainage area had to be stabilized prior to directing water to the pervious concrete area. Aggregates contaminated by dirt from the surrounding construction zone were to be removed and replaced with clean aggregates. The storage area must drain within 48 hours and observation wells were placed to monitor the draining ability.

For the maintenance of the pervious concrete over time, it was noted by the site designers that it is difficult to prescribe specific types of maintenance tasks and the frequency at which they should occur. It was mentioned that annual dry-weather sweeping in the spring months would be important. Vacuuming without water spray was recommended noting that spraying may lead to subsurface clogging. An annual spring maintenance inspection was recommended that would include:

1. Measurement of drawdown rate at the observation well 3 days after a storm event of greater than ½ in. Any standing water at the 3-day check would indicate a clogging problem.

2. Check for evidence of sediment deposition, organic debris, staining, or ponding that could result in clogging. If clogging is identified, a vacuum sweeper without brooms or spray should remove the deposited material. Test the area by pouring water from a 5-gallon bucket.
3. Inspect the surface of the pavement for signs of surface deterioration such as cracking or spalling. Replace or repair the damaged areas before the spalled concrete can clog the pores of the rest of the pavement.
4. Inspect the contributing drainage area if any source of sediment or erosion is detected. As an example for inspection checklist, Appendix C of Chapter 9 of the Virginia Stormwater Management Handbook (2010) is noted (VADEQ 2013a).

Sampling

On August 26, 2015, a visit was made to the Stringfellow jobsite to observe the placement and sample the concrete. At the jobsite, the density test on the fresh concrete indicated a value of 136.8 lb/ft^3. Six round slabs, four 12 in diameter and two 18 in diameter, all of which were 6 in in height, were made using different compaction methods such as tamping, hand float, and proctor hammer. The samples were covered with plastic and kept at the jobsite for 7 days, after which they were brought to the laboratory and kept in the moist room for final curing. The samples were weighed and the dimensions taken as they arrived. These samples were also used to determine the infiltration rates in accordance with ASTM C1701.

On June 20, 2016, a second visit was made to the Stringfellow jobsite to observe the condition of the pavement after several months of use and also to test the infiltration rates of the lot. Visual inspection was conducted for the pavement condition. ASTM C1701, shown in Figure 1, was used to determine the infiltration rates of the lot.

Figure 1: Stringfellow Park and Ride checkup 6 months after placement using ASTM C1701 for infiltration rate

The sites for measurement of the infiltration rate were intentionally spaced apart and taken at various locations within the parking stalls. For example, one measurement would be taken near the joint with the asphalt while another measurement would be taken within in the stalls or closer to the curb, farthest from the asphalt driving lane.

4.1.2 - Reston Parking Lot

At the Reston District Police Department parking lot, the mix design given in Table 5 was used by the same contractor who constructed the Stringfellow Park and Ride. A trip was made on November 2, 2015 to observe the placement and sample the concrete. The same placement methods and site preservation were used as in the Stringfellow project. Specimens of 6 in height, three of which had 12 in diameter and two of which had 18 in diameter, were consolidated using the vibrating hammer or with the proctor hammer, as shown in Figure 2.

Figure 2: Reston District Police Station parking lot specimen preparation using various compaction methods

These specimens were also prepared and cured at the project site for 7 days. In addition to ASTM C1688 for fresh concrete density, ASTM C1701 for the infiltration rate of in-place concrete was conducted on the specimens.

The Reston lot was also visited again on June 20, 2016 to observe the pavement condition and take measurements of its infiltration rates using ASTM C1701. Again, measurements were distributed about the site to explore the range of infiltration rates within the parking lot.

4.2 - VTRC Lab Work

As part of the laboratory work on PC in the VTRC lab, various mix designs were developed based on those used at the Stringfellow and Reston projects, those presented in other reports, the American Concrete Institute’s ACI 522R, and also the NRMCA mixture proportioning guide (ACI 2013; Wang et al. 2006). The mix proportions were intentionally simplified and did not include optional ingredients such as dispersed fibers for reinforcement or supplementary cementitious materials. Though fibers and small amounts of sand have been reported to do well in pervious concrete, their presence decreases permeability. The mixes chosen were analyzed for material properties used as the potential acceptance tests in field applications of PC. Specifically, the properties examined were fresh and hardened densities, void content, abrasion resistance, infiltration rate, and hydraulic conductivity. Of these tests, the density and void content, abrasion resistance, and infiltration rate were measured using their respective ASTM procedures specifically designed for pervious concrete as summarized in Table 4. The hydraulic conductivity was calculated using an ASTM procedure for soils testing modified for applications with PC.

Properties not typically used for acceptance tests were also examined. These included compressive strength (ASTM C39) and splitting tensile strength (ASTM C496) (ASTM 2011; ASTM 2004). The strengths testing have no ASTM procedures specific to PC, but use tests for conventional concrete mixes. Another aspect of the concrete study was the comparison of placement techniques. For example, the consolidation methods of rodding, Proctor hammer, and Marshall hammer were all compared for repeatability in the resulting density measurements of the specimens.

4.2.1 - Infiltration Rate

The infiltration rate of PC was determined on specimens brought from the field using ASTM C1701. To begin, the concrete was saturated with 8 lbs of water. To carry out the test properly, the water level was kept between two parallel lines on the inside of the infiltration ring. If the water took 30 seconds or longer to travel through the specimen, then an additional 8 lbs of water was infiltrated and the time of infiltration recorded. If the water in the initial 8 lbs took less than 30 seconds to infiltrate, an additional 40 lbs of water was added using the same procedure. The infiltration ring has a conversion chart that indicates the infiltration rate of the specimen according to how long 40 lbs of water takes to travel through the specimen. However, to determine infiltration rates if 8 lbs of water is used on the infiltration test, the value on the chart has to be divided by 5 since the conversion chart is specifically for 40 lbs. Figure 3 shows the infiltration ring being used on a lab specimen brought from the field. The large 12 inches and 18 inches in diameter specimens were made in the field to determine the infiltration rates.

Figure 3: ASTM C1701 on lab specimen wrapped in tape and secured with plumber's putty to prevent leakage from edges

The following summer, the in-place concrete at the field sites was tested using ASTM C1701. In Figure 4, an infiltration ring is secured to the pavement surface with plumber's putty, ready for testing.

Figure 4: ASTM C1701 infiltration rate test on in-place concrete

4.2.2 - Mix Designs

After the Stringfellow project, a batch was made in the VTRC laboratory on September 23, 2015 using the same ingredients except that the same type of portland cement was obtained from a different source. This is denoted as Batch 1 in Table 6, which had the mixture proportions used in the field projects. In the beginning, the density of the fresh concrete was determined using both the Proctor and Marshall hammers in conformance with ASTM C1688. Also, a density test was conducted using the vibrating hammer used to consolidate roller compacted concrete described in ASTM C1435; the goal of this adjusted test was to determine similar densities as obtained using the standard Proctor and Marshall hammers and to introduce the vibrating hammer to enable compaction of larger specimens efficiently. When the vibrating hammer was used, duration of compaction was varied until similar density to standard test procedure (ASTM C1688) was achieved. This time duration was that used in compacting field specimens in the field. The other laboratory batches, shown in Table 6, were made with varying proportions to obtain void contents ranging from about 15 to 25%. The water-cementitious material ratio was kept as in the field projects at 0.33. In two of the batches, small amounts of sand were used to reduce the void content. The batches presented in Table 6 underwent the testing methods such as density, strength, abrasion resistance, and hydraulic conductivity, outlined in the following sections. For the mix designs, a multivariate analysis was conducted and showed that simple regression was appropriate to determine which element of the mix had the greatest impact on void content of the pervious content. For the material properties such as strength, density, and infiltration rate, a simple regression analysis was performed in SPSS and Microsoft Excel to confirm the correlation with the other properties.

Table 6: Laboratory batches to investigate relationships between void content and mix ingredients (PC: portland cement, CA: coarse aggregate, w/cm: water-cementitious material ratio)

Batch	Date	PC lb/yd^3	CA #8 aggregate 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

*Batch 5 has 129 lb sand; Batch 10 has 173 lb sand

4.2.3 - Fresh Density and Void Content

Fresh density of PC is determined using ASTM C1688 and is heavily dependent on compaction methods, of which two possibilities have been identified in the ASTM procedure; one compaction method (A) uses the Proctor hammer while the other compaction method (B) uses the Marshall hammer (Anderson, et al. 2013; ASTM 2014). This test requires the volume of the bucket, generally the bowl of the pressure air meter, shown in Figure 5 and the mass of the specimen.

Figure 5: Fresh concrete density test using ASTM C1688 which provides the density of the material by dividing mass of the specimen by its volume

With a typical void content of 15 – 25%, the fresh density of PC can be around 129 lb/ft^3, though actual values depend on the specific mix design, compaction efforts, and infiltration needs (Kevern et al. 2006). For the VTRC tests, the fresh PC specimen tested for density was placed in the pressure meter bucket in two lifts, and each lift compacted with 20 blows from the Proctor hammer. Using the measured density and the theoretical density, the void contents of the fresh samples were determined. Theoretical density is the density as if the specimen is free of air voids. The value of “percent voids” is the difference between the theoretical and the measured density divided by the theoretical density and then multiplied by 100.

4.2.4 - Hardened Density and Void Content

Hardened density of PC is determined using ASTM C1754 and, like the fresh density, is heavily dependent on the compaction efforts. There are two methods available to measure hardened density; the first method uses a lower temperature (100 °F) to dry the specimens for a longer amount of time while the second method uses a higher temperature (230 °F) for a quicker drying period. The second method is somewhat destructive to the sample, however, and further testing (such as for strength) of that sample is not allowed. In the VTRC lab, 4x8” cylinders were used and the specimens were dried using the first technique and each dried mass was recorded. An example of a specimen used for hardened density and void content is shown in Figure 6.

Figure 6: Hardened concrete density specimen for ASTM C1754 which uses the dry mass of the specimen and the geometry of the specimen to determine the density

After drying, each specimen was submerged for 30 minutes and tapped with a hammer to release bubbles from the voids. The mass of each submerged specimen was then recorded. The calculation to determine hardened density is given in **Equation 1**, as provided in ASTM C1754 (ASTM 2015b). In this equation, K represents a conversion factor, A represents the dry mass of the specimen, D represents the diameter, and L represents the specimen length.

$$\boldsymbol{Density = \frac{K*A}{D^2*L}} \qquad \text{Equation 1}$$

The void content of hardened pervious concrete is determined by **Equation 2**, listed below. In **Equation 2,** the variables are the same as **Equation 1**, except B represents the submerged mass of the specimen and ρ_w represents water density of the bath.

$$\boldsymbol{Void\ content = \left(1 - \frac{K*(A-B)}{\rho_w*D^2*L}\right) * 100} \qquad \text{Equation 2}$$

4.2.5 - Compressive Strength

Since there is no standard ASTM method for testing the compressive strength of pervious concrete, the methods used for conventional concrete, ASTM C39, are used. The samples used for compressive strength testing were 4” x 8” as shown in Figure 7.

Figure 7: Compressive strength testing for ASTM C39 which uses the load divided by the cross-sectional area of the specimen

Sample preparation had to be modified from the standard consolidation used for regular concretes. For regular concretes, sample preparation follows ASTM C31; cylinders are consolidated in two layers either by rodding or mechanical vibration. However, the PC cylinders were compacted using the Marshall hammer such that 5 drops were delivered onto each of the two layers. The selection of 5 drops was to simulate similar compaction effort as the fresh density tests using the pressure air meter bowl; the ratio of surface areas indicated 5 blows for the cylinder versus the 20 blows for the bowl.

4.2.6 - Splitting Tensile Strength

To determine the splitting tensile strength of pervious concrete, ASTM C496 was used. This test procedure setup is shown in Figure 8.

Figure 8: Splitting tensile strength using ASTM C496 where a diametral compressive force is applied along the length of the specimen

The splitting tensile strength test is useful for pervious concrete because it is not as heavily influenced by the vertical distribution of density values created by the compaction method of the proctor hammer. Since the testing is conducted on the long-edge of the specimen, the results are believed to not be as skewed as the upright test of ASTM C39. Like the compressive strength test, the specimens are 4” x 8” and were prepared by the same procedure as outlined in ASTM C31 except that Proctor hammer was used. To determine the splitting tensile strength, **Equation 3** (given in ASTM C496) was applied.

$$\boldsymbol{T = \frac{2*P}{\pi*l*d}} \qquad \text{Equation 3}$$

In **Equation 3**, T is the splitting tensile strength (psi), P is the maximum applied load as indicated by the machine (lb_f), l is the specimen length (in), and d is the specimen diameter (in).

4.2.7 - Impact and Abrasion Resistance

The ability of the PC to resist degradation from impact and abrasion is measured by ASTM C1747. The 4” x 4” cylindrical specimens of known mass were tumbled in the Los Angeles machine, three at a time, for 500 cycles without the steel balls. The results of the abrasion test after 500 cycles are shown in Figure 9. Once the cycles were complete, the final mass of the concrete that could be contained on a 1” sieve was taken. The amount of material left behind was subtracted from the initial mass and the difference was taken as the percent mass loss.

Figure 9: Abrasion test specimens using ASTM C1747 which tumbles the three specimens for 500 revolutions in the Los Angeles machine

4.2.8 - Hydraulic Conductivity

Hydraulic conductivity of laboratory cast 4x8 inch cylindrical specimens was determined using a falling head permeameter constructed at the VTRC. Figure 10 shows the falling head permeameter for measuring how conducive the PC sample is to the movement of water.

Figure 10: Falling head permeameter constructed based on ASTM D5084 and enables testing of specimens with 4" diameters

To begin, the specimens were first saturated in a fresh water bath for at least 30 minutes. Then, the vertical sides of the 4" x 8" cylinder were shrink-wrapped and then placed in the left side tube and secured in place. The clear cylinder was secured above the specimen. Next, the white tube on the right-hand side of the picture was filled until water seeped up through the PC sample, as indicated by water escaping through the overflow opening which is about 10 mm above the elevation of the top of the concrete sample. This backfilling was to saturate the specimens and to eliminate any trapped air bubbles. Once this overflow was achieved, the valve was closed and the clear cylinder above the concrete specimen was filled 10” above the specimen surface. The valve was then opened and the time it took for the water level to drop a distance of 8” was recorded.

4.2.9 - Recovery after Clogging

To examine the ability of pervious concrete to recover its infiltration capabilities once clogging materials have been introduced to the system, a procedure was devised to intentionally clog the pores of the specimens. The clogging solution, shown in the permeameter in Figure 11, consisted of 20 g of clay and 20 g of sand in 2 L of water.

Figure 11: Falling head permeameter with clogging solution (20 g clay and 20 g sand in 2 L water) to investigate the clogging and cleaning procedures

The set-up for the tests for recovery after clogging followed a similar order of events as the simple hydraulic conductivity test procedure. Initially, the clogging solution filtered through the sample and then clean water was introduced into the clear cylinder above the specimen and the time it took to drop 8” was recorded. Then, after the sample was vacuumed, again clean water was infiltrated through and timed. The third step was percolating water through and timing after power washing and vacuuming the sample. This procedure resulted in four time recordings for one sample: clean water in clean sample, clean water after clogging the sample, clean water in vacuumed sample, and clean water in the power washed and vacuumed sample.

5.0 - Results

The results of the tests conducted on the pervious concrete field samples in the laboratory and at the sites and also the laboratory specimens prepared in the VTRC are presented in this section. Not only do the results indicate the characteristics of the analyzed batch, but they also indicate which tests can be used in the field by VDOT to ensure that the batch has sufficient qualities such as satisfactory infiltration and good durability. Knowing how factors such as fresh density or cementitious content affect pervious concrete performance in infiltrating water and in attaining strength and abrasion resistance can help in the placement phase because it indicates to a technician if a mix will perform well. Contents of this section include the fresh and hardened density and void contents, mixture proportions as they relate to void content, abrasion resistance, and strength as it relates to density and cementitious content.

5.1 - Field Placements

Various compaction methods are available for pervious concrete and, depending on how the methods are executed, the final density of the specimen will vary. At the Stringfellow project, six pervious concrete samples, cylinders of 12” or 18” diameter and 6” height, were cast using the compaction methods listed in Table 7.

Table 7: Infiltration rate specimens from the Stringfellow project subjected to various compaction methods and analyzed for density and void content

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 top	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 top	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*

As is seen with specimens 1 and 2 and also 3 and 5, even the same compaction method can produce varying results in density due to the varying pressure imparted during compaction and therefore will likely influence void content and infiltration rates in the field. Different compaction efforts of the specimens resulted in densities ranging from 137.5 to 145.4 lb/ft^3 for the wet density and from 136.2 to 143.9 lb/ft^3 for the dry density. Wet density was measured after one month in the moist room where water jets provide dripping water over the specimens. After the wet density, specimens were dried in the lab at a relative humidity of 50% for 1 week. The void contents, calculated based on the theoretical density of 170.8 lb/ft^3, are shown in Table 7 along with the dry densities. Average void content (18.0%) was slightly below the target air content of 19.7% shown in Table 5. The 18” specimens were created for analysis of the infiltration rate test to identify any lateral leakage through the specimen that may alter the infiltration rate results.

A similar exploration of compaction methods was conducted at the Reston project, though the compaction methods were different from those used in Stringfellow. Table 8 presents the density values of the pervious concrete placed at Reston. For similar reasons to the Stringfellow project, both 12” and 18” specimens were formed. The wet density values presented in Table 7 and Table 8 were taken after the specimens sat in the moist curing room for one month. The dry density values were taken following a week of drying in the lab after the one month spent in the moist room. The void contents (averaging 13.7%) were lower (averaging a 24% reduction) when compared to the Stringfellow project; this is likely due the application of greater pressure on the specimens with the introduction of a roller.

Table 8: Infiltration rate specimens from the Reston project subjected to various compaction methods and analyzed for density and void content

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*

5.2 - VTRC Lab Work

This section presents the results of the laboratory analyses conducted on the cylinders from the jobsites and also those mixed in the lab. The infiltration rate tests used the field specimens that had varying void contents which resulted from the different compaction efforts. All of the other analyses used the lab mixes which maintained consistent compaction efforts but whose void contents varied as a result of the mix designs.

5.2.1 - Infiltration Rate

For seven days, the specimens from the field projects were left at the site and allowed to cure under plastic covering to prevent moisture loss. At the end of the week the specimens were measured for density using their mass divided by volume; volume was determined from the diameter which was constant due to the dimensions of the mold and the height which was determined by caliper measurements at 6 points around the specimen. For the three specimens made in the lab, the same procedure was followed. Then, in accordance with ASTM C1688, the void content of each specimen was determined using the theoretical density and measured density. Figure 12 shows the infiltration rates plotted against their corresponding void contents. The results show strong non-linear correlations between infiltration rates and void contents. Shown in Figure 12 are only the 12” diameter specimens. The 18” specimens were omitted from this analysis for comparability of results. If performed by a single operator, the uncertainty associated with this infiltration rate test is 4.7% (ASTM 2015a).

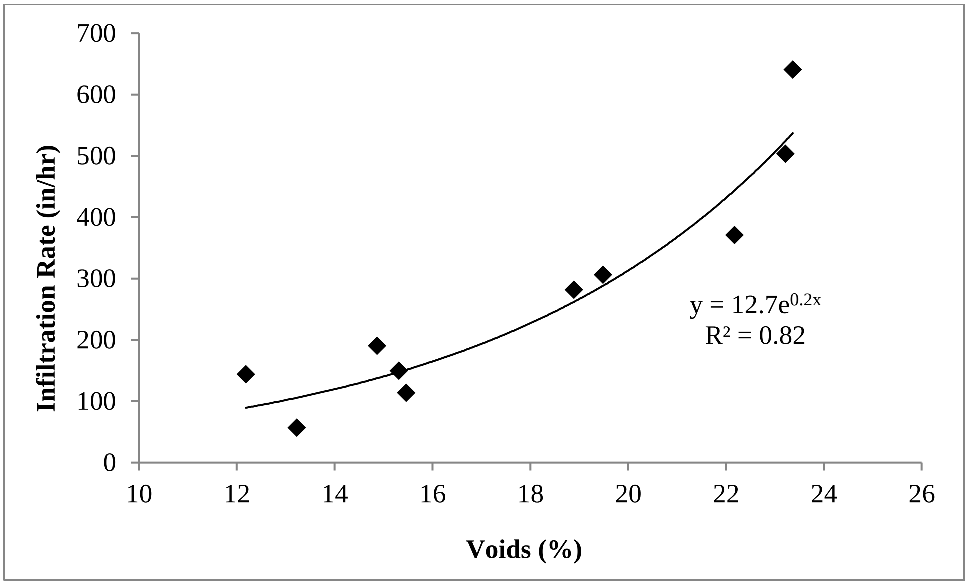

Figure 12: Infiltration rate (in/hr) and void content (%) of specimens prepared from one mixture and various compaction efforts

Infiltration rates were also measured in the field approximately 6 months after construction. It was determined that there was very high variability of infiltration capabilities within the lots even when only 50 ft separated each tested spot. Even though the same compaction by the same crew was done, in each project, there was high variation in the infiltration rates. In the two field projects, the infiltration rates varied from 21 to 820 in/hr. Of these values, more than two-thirds were over 100 in/hr, the value that Wisconsin uses for their guidelines as an acceptable infiltration rate (WisDOT 2012).

5.2.2 - Mix Designs

On September 23, 2015 immediately following initial observations at the Stringfellow project, a batch of pervious concrete was mixed using the same mix design in the VTRC laboratory space. The density test of this batch with the Proctor hammer yielded 126.4 lb/ft^3 and the test with Marshall hammer gave 126.0 lb/ft^3. Based on the theoretical weight of 170.8 lb/ft^3, a void content of 26% was determined. This high value is attributed to the stiffening of the mixture since several readings were taken to familiarize with the hammers and to determine the repeatability of the tests. This batch is identified as “Batch 1” in Table 9. Then, after the Reston project, additional mixtures were made and subsequent density testing was conducted, also presented in Table 9. The w/cm was 0.33 as in the field projects.

Table 9: VTRC Lab Mixes with various mix ingredients to obtain various densities and void contents

Batch	Date	pc	#8 aggreg.	water	w/cm	Voids %	Density (lb/ft^3)			Measured Voids %
							Design	Theo.	Meas.	
1	9/23/15	550	2972	182	0.33	19.7	137.2	170.8	126.4	26.0
2	12/7/15	660	2725	216	0.33	19.7	134.9	166.4	136.4	18.0
3	12/7/15	570	2884	188	0.33	19.7	134.9	168.6	134.4	20.3
4	12/14/15	700	2884	231	0.33	15	141.3	166.2	138.4	16.7
5	12/14/15	600	2884	129	0.31	16.7	140.7	168.9	138.4	18.1
6	12/14/15	492	2784	162	0.33	25	127.4	169.8	131.2	22.7
7	12/15/15	674	2933	223	0.33	15	141.9	166.9	140.0	16.0
8	12/15/15	544	2933	180	0.33	20	135.4	169.3	130.8	22.7
9	12/15/15	414	2933	137	0.33	25	129.0	172.0	131.2	23.7
10	12/15/15	600	2933	198	0.33	13.6	144.6	167.4	138.8	17.1
11	12/17/15	648	2983	214	0.33	15	142.4	167.5	136.2	18.7
12	12/30/15	700	2884	231	0.33	15	141.3	166.2	144.0	13.4
13	12/30/15	410	2946	135	0.33	25	129.3	172.3	127.2	26.2
14	1/20/16	388	2983	128	0.33	25	129.6	172.8	129.2	25.2
15	1/20/16	700	2884	231	0.33	15	141.3	166.2	145.6	12.4
16	1/20/16	544	2933	180	0.33	20	135.4	169.3	136.4	19.4

The sixteen batches mixed in the VTRC lab were used for the analyses presented in this chapter. With the fresh and hardened density testing, comparisons were made for the laboratory batches between amounts of coarse aggregates (CA) and portland cement (PC) material, strength, and hydraulic conductivity. The infiltration rates of the field samples and three lab samples were also compared as a function of density values.

The goal of exploring mix designs was to analyze variables which influence the void content produced in the concrete specimens. Due to constraints in the laboratory space at VTRC, one repetition of each mix design was conducted and each batch was assumed to be representative of the associated mix design. The dependent variable, void content (%), is normally distributed and therefore linear regression analysis is appropriate for statistical evaluation. The three independent variables selected for their influence on void content were cement content, coarse aggregate content, and water content. With the w/cm ratio kept constant, the water and cement contents cannot be assumed to be linearly independent and consequently were not used in the same multiple regression analysis on voids. Therefore, the two independent variables explored through multiple regression analysis were the portland cement and coarse aggregate contents.

The multiple regression linear model created in Microsoft Excel is shown in Table 10 in the “CA and PC” predictor row along with its adjusted R^2 which accounts for multiple independent variables. In general, the R^2 indicates the proportion of variance of void content that is explained by the independent variables of CA and PC. In this table, x_1 is the coarse aggregate (CA) content while x_2 is the portland cement (PC) content. Table 10 also reports the p-values associated with the multiple regression model; if the p-value is less than 0.05, there is enough evidence, with a 95% confidence, to reject the claim (hypothesis) that the independent variable(s) have no correlation with the dependent variable of void content. If greater than 0.05, there is not enough evidence to reject the hypothesis. Since “CA and PC” model indicates that the CA is not important to the model (high p-value for x_1) and the overall p-value indicates that the whole model is not a good fit, a regression analysis of just PC and voids was conducted. These results are shown in the last row of Table 10 and the high R^2 value and low p-value indicate that PC alone is a good predictor.

Table 10: Regression analysis results using one dependent (void content) and two independent variables (x_1 = coarse aggregate (CA) and x_2 = portland cement (PC))

Independent	**Model**	R^2	**p-value**		
			x_1	x_2	Whole model
CA and PC	$voids = 32.8 + 0.0025x_1 - 0.035x_2$	0.75 (adj.)	0.77	2.5×10^{-5}	0.23
PC	$voids = 40.31 - 0.0357x_2$	0.78	1.9×10^{-9}		

As shown in Table 10, the predictor (independent variable) with the highest correlation and lowest p-value is PC content. Figure 13 shows the relationship between the two variables graphically. As cement content increases, void content steadily decreases. Lower void content is associated with higher cementitious content as more paste fills the voids, thus making the concrete denser.

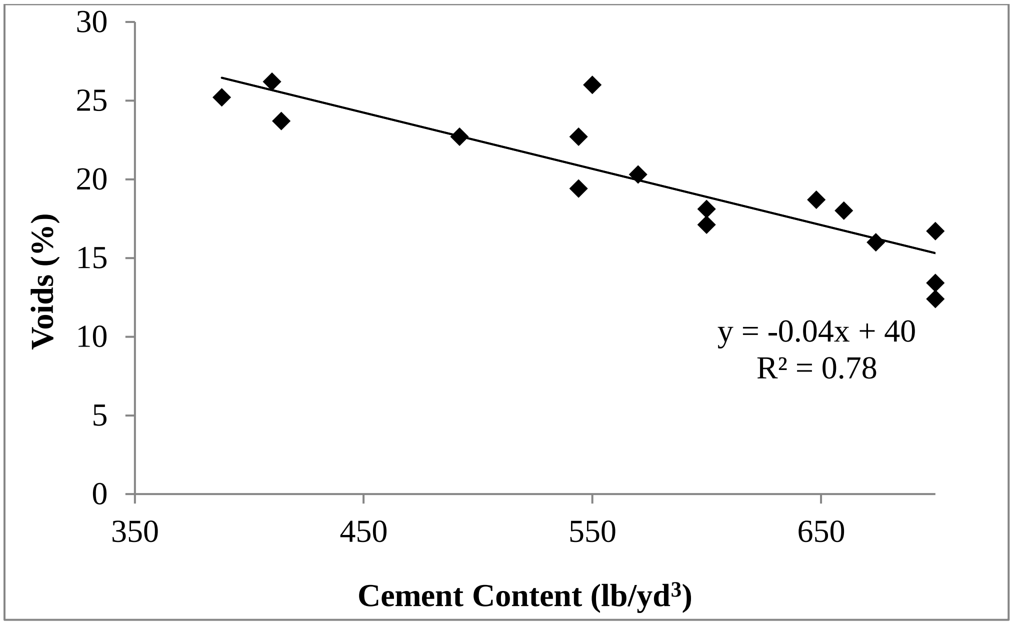

Figure 13: Relationship between voids and cementitious content obtained from regression analysis

5.2.3 – Density and Void Content

The design density is the density predicted by the mix design. Figure 14 compares the design density to the measured density and indicates a relationship between the two such that measured density is only representative of design density about half of the time. This is due to the variability imparted by the compaction effort to different mixtures. According to the ASTM standard procedure (ASTM 2014), the variability in these results is 1.4 lb/ft^3.

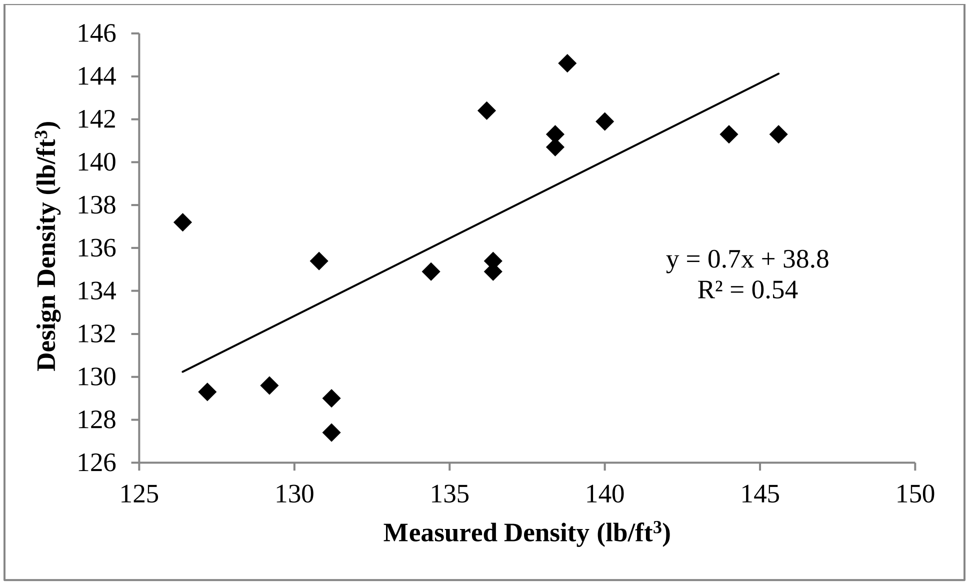

Figure 14: Design density and measured density of VTRC lab specimens

Void content of a pervious concrete sample is calculated directly from its measured density, so quantifying the correlation of void content and density is not useful. Select results in the remainder of this chapter are presented using the density of the concrete, rather than void content, as this is the standard expected in the field of concrete technology.

5.2.4 - Strength

The compaction on the vertical axis within a specimen of pervious concrete can vary, thus making compressive strength results unreliable. Because of this variability, and also because strength testing of pervious concrete is not standardized, compressive strengths are not used as quality assurance or acceptance standards for many PC projects (ACI 2013, NRMCA 2016b). However, strength of pervious concrete in general is indicative of the material's durability, a quality essential for any stormwater management system. Higher compressive strength values are associated with higher cement content, as shown in Figure 15; however, variability in the results is high. Cement contents of specimens ranged from 400 to 700 lb/yd^3. As was seen previously (Figure 13), higher cement content leads to lower void contents which is generally associated with higher strengths.

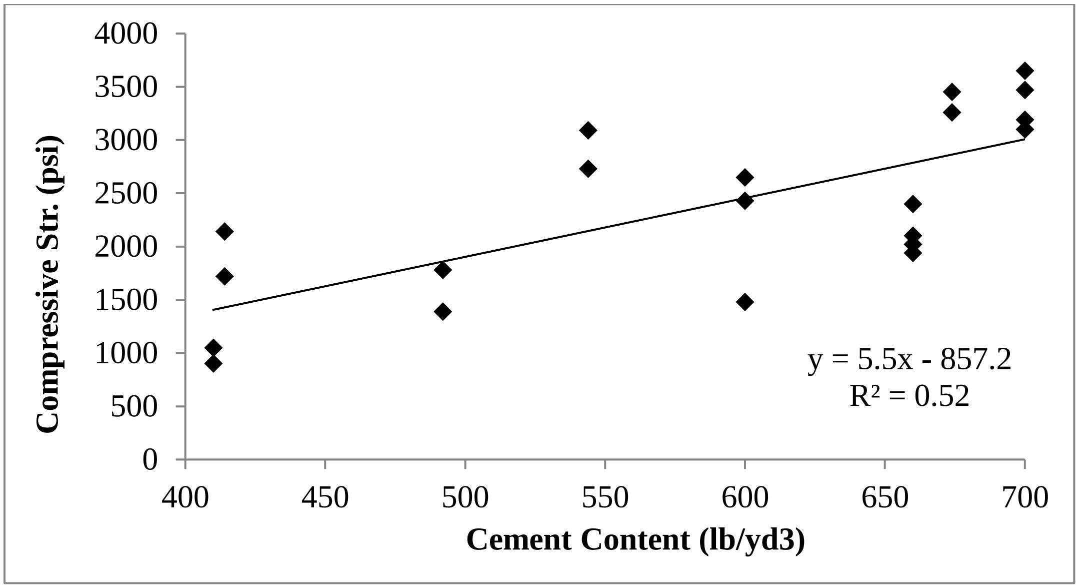

Figure 15: Relationship between compressive strength (ASTM C39) and cement content of the laboratory mixes

In addition to the cement content, hardened specimen density (ASTM C1754) was also compared to compressive strength, as seen in Figure 16. Specimen density has a fairly strong correlation with compressive strength, even with the high variability seen with the cement content in Figure 15. The density values of these specimens ranged from approximately 126 to 145 lb/ft^3.

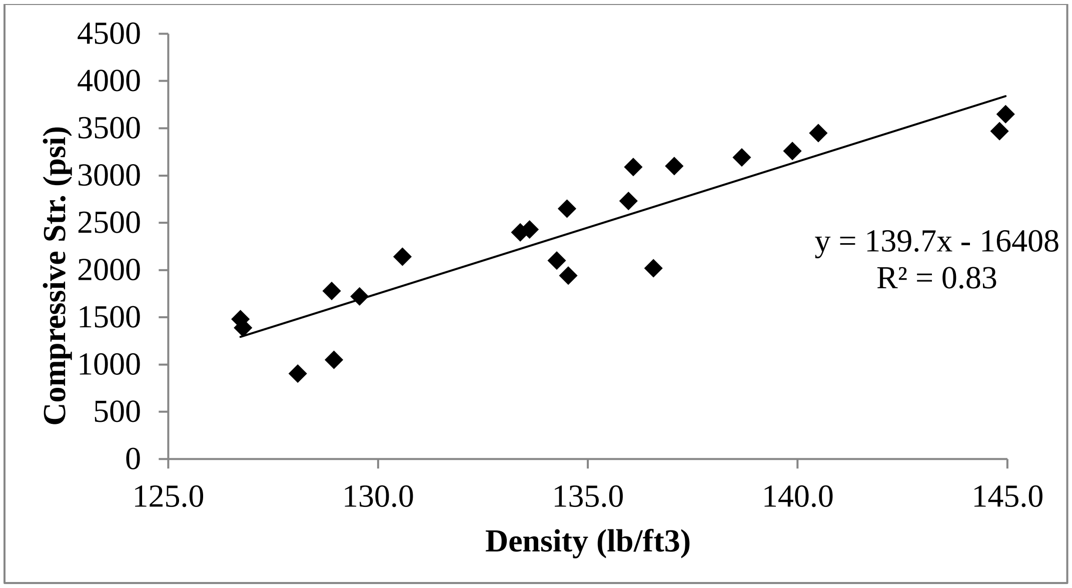

Figure 16: Relationship between density and compressive strength (ASTM C39) of the VTRC laboratory mixes

In order to take into account the vertical distribution of compaction from consolidation methods, the splitting tensile strengths of the specimens were measured. These results relating hardened specimen density (ASTM C1754) to splitting tensile strength are presented in Figure 17.

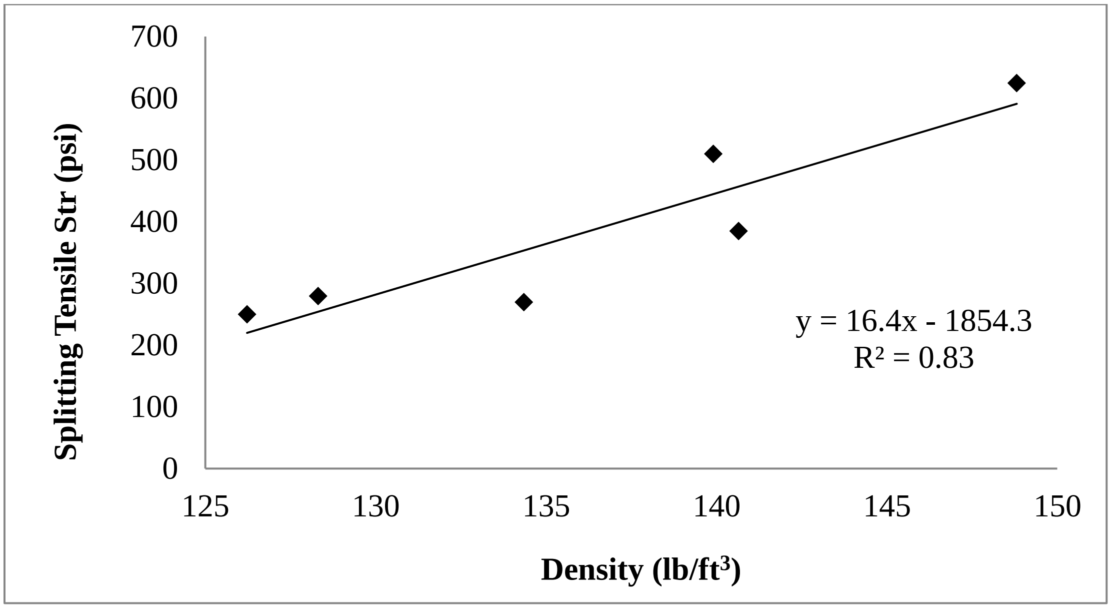

Figure 17: Relationship between density and splitting tensile strength (ASTM C496) of the VTRC laboratory mixes

Fewer specimens were formed for splitting tensile strength, so these results are limited compared to the compressive strength tests. However, the relationship between density and splitting tensile is still clear in that higher density results in higher strength. With these tests, the density of the specimens ranged from approximately 126 to 149 lb/ft^3.

5.2.5 - Impact and Abrasion Resistance

The void content in pervious concrete results in inherently lower strengths than conventional concrete. Therefore, with the application of pervious concrete as a pavement, understanding its durability in terms of abrasion and impact resistance is a major concern. The results of the impact and abrasion test conducted according to ASTM C1747 are given in Figure 18. As density increases and void content decreases, the percent mass loss decreases. These results of the impact and abrasion tests reflect those of the strength tests. Higher void content (and likely higher infiltration rates) generally leads to lower durability. These results are important because, when designing a pervious concrete pavement system, the tradeoff between infiltration capabilities and durability is a driving factor. The ASTM manual states that the error expected from this test procedure is 1.3% (ASTM 2015c).

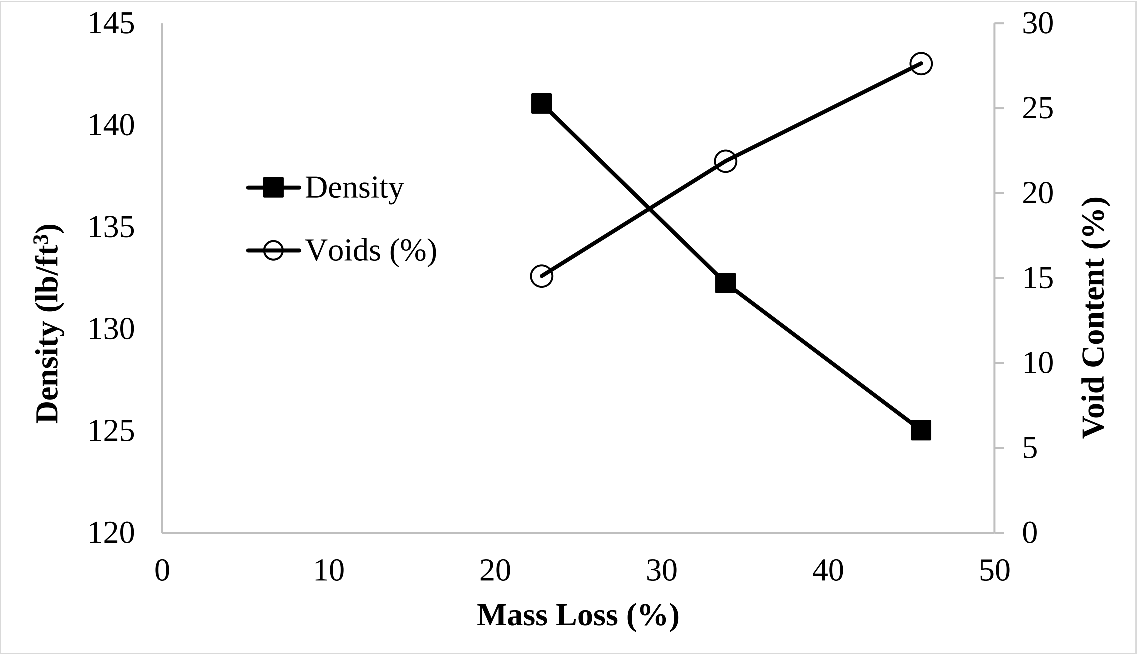

Figure 18: Relationship between mass loss and void content or density obtained from the VTRC laboratory mixes using ASTM C1747

5.2.6 - Hydraulic Conductivity

The ability of pervious concrete to infiltrate stormwater runoff is the most essential characteristic of the material. In addition to infiltration rates, infiltration capabilities can be described by hydraulic conductivity. As shown in Figure 19, hydraulic conductivity as it relates to specimen density can be described as an exponential curve.

When pervious concrete is used as a pavement, however, it is likely that clogging materials carried by vehicular and pedestrian traffic and possible debris carried onto the impervious surface from nearby pervious areas will be introduced to its surface. Therefore, it is valuable to understand the process by which infiltration rates can be recovered once clogging materials such as sand and clay are present in the medium. The results of the clogging and cleaning procedure are present in Figure 19. Figure 19 contains four sets of data: (1) the blue diamonds represent the initial hydraulic conductivity (k) prior to any clogging material, (2) the green squares represent the hydraulic conductivity of the concrete after the solution containing sand and clay (as described in the

Methods section), (3) the red triangles represent the hydraulic conductivity after one vacuuming, and (4) the black circles represent the hydraulic conductivity after both pressure washing and vacuuming. The vertical lines on the graph are meant to assist in identifying density values of the specimens and therefore which results belong to the same specimens. Table 11 summarizes the best-fit lines and the corresponding R^2 for each condition.

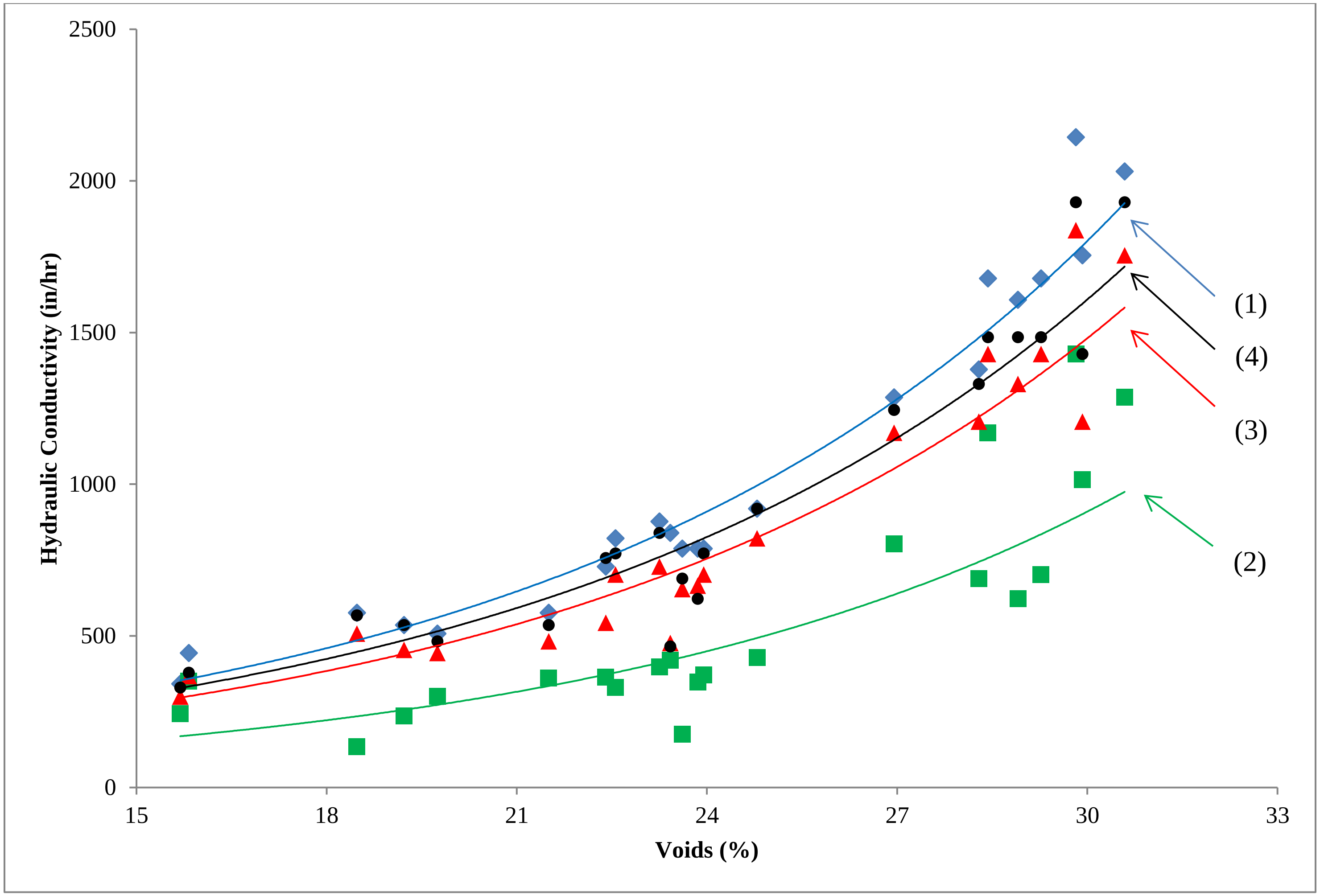

Figure 19: Hydraulic conductivity values (k) with respect to treatment and void content of VTRC lab mixes as measured using the falling head permeameter - (1) the blue diamonds represent the k prior to any clogging material, (2) the green squares represent the k of the concrete after the solution containing sand and clay, (3) the red triangles represent the k after one vacuuming, and (4) the black circles represent the k after both pressure washing and vacuuming

Table 11: Best fit exponential lines for hydraulic conductivity values of VTRC lab specimens after their respective cleaning procedures

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

At lower density values, the hydraulic conductivity drops drastically with the introduction of the clogging solution. Not only do the hydraulic conductivity values at these density values drop, but the correlation between density and hydraulic conductivity is not as well defined as it was initially. As the density decreases below 130 lb/ft^3 (and void content increases) there is a high variability in the results. However, at the higher density values, relatively little change is seen in the infiltration capabilities even after clogging and cleaning procedures. At the lower density values, improvements in the hydraulic conductivity values are present after just one vacuum cycle of the sample. Similar results are prevalent after vacuuming and power washing as well. In most of the specimens, the highest hydraulic conductivity achieved is the initial value, followed by pressure washing and vacuuming, then just vacuuming, and finally clogging as the lowest value.

6.0 - Discussion

Pervious concrete has been used successfully as a stormwater management tool throughout the Commonwealth of Virginia. The project goal of this study was to conduct the necessary literature review, field observations, and laboratory analyses to develop a special provision so that VDOT could also use pervious concrete as a stormwater management practice for low-volume traffic applications. The two field observations, located in Fairfax County, Virginia, provided valuable insight into the construction procedures and necessity of maintenance of this special type of concrete. The properties of pervious concrete explored in this paper included density, infiltration capabilities, mix design, strength, durability (abrasion resistance), and hydraulic conductivity. In addition to these material properties being analyzed, relationships between the properties were also studied so as to gain a better understanding of how they influence one another and how to use these relationships to achieve a better product in the field.

6.1 - Field Sites

The analyses of the samples taken from the Stringfellow and Reston parking lots indicate variability in densities which resulted in variable infiltration capabilities. Even though at both locations the same compaction method and efforts of the vibrating roller in addition to the perpendicular roller were used on the larger scale of the parking lots, there was still spatial heterogeneity within each parking lot. From this result, it is clear that even within the same project with all factors controlled and monitored, the infiltration rate did not stay constant spatially. Factors that may influence variability of infiltration rates within a project could include changes in vibrating roller operators, over consolidation or under consolidation, or too long of a delay in the process of mixing, placing, and curing. Additionally, it was evident that the parking lots had not been cleaned in some time and therefore debris on the surface was likely influencing the infiltration rates.

6.2 - VTRC Lab Work

The development of the special provision and the requirements it contains are based on experiences within Virginia that are attainable with locally available materials and equipment. Understanding how the material properties of pervious concrete relate to one another is essential for developing effective procedures for mix design and placement. Being a stormwater management tool, the most important characteristic of pervious concrete is that it does infiltrate runoff at a reasonable rate. Therefore, understanding the relationships between infiltration capabilities and qualities such as void content and cement content are crucial when it comes to implementation.

In terms of density, the value of measured hardened density of the specimens was used to calculate the respective void content, so the direct comparison of cement content to voids can be extended to density as well. In terms of mix design, cement content had the greatest influence on void and density compared to coarse aggregate content. This is a helpful comparison because, when designing a pervious concrete system, the void content is one particularly important driving parameter. Being able to predict the void content through analysis of the mix design would be helpful. In fact, coarse aggregate content had no recognizable influence on void content of the specimens.

Being able to predict infiltration rates through the measurement of a specimen's density is also quite valuable in terms of field work and quality assurance. In this study, over 80% of the void measurements were reflective of the specimen's infiltration rates on an exponential line of best fit. Similarly, the hydraulic conductivity had over 90% relationship to the specimen void content. There was variability, which is likely due to the fact that these properties are dependent on both mix design (i.e. cement content) and compaction method.

Durability of pervious concrete, or its ability to withstand stressors such as freeze-thaw cycles, chemical attacks, impact and abrasion, raveling, or scaling, is an area of significant concern given the intrinsically high void content of pervious concrete. It was found that lower strengths and abrasion resistance were attributed to higher void contents and thus lower paste contents. However, achieving high durability and also high infiltration capabilities is a difficult process as the relationship of durability and infiltration is a significant trade-off of pervious concrete. It may be possible to better optimize both of these characteristics through adjustments to the mix design such as the inclusion of fine aggregates and fibers.

The primary goal of the hydraulic conductivity testing in the falling head permeameter was to determine the ease with which the effects of clogging can be reversed. After the clogging solution percolated through the specimens, the cleaning procedure was conducted with good results. In the higher densities (fewer voids), the clogging solution of sand and clay had relatively little influence on the hydraulic conductivity values. This is likely because the sediment was less likely to find its way into pores given the relatively infrequency of them. However, at lower densities (more voids), below 130 lb/ft^3, the clogging solution had a noticeable impact and resulted in high variability of the hydraulic conductivity results. Overall, it was determined that it is possible to recover infiltration capabilities even after clogging materials have been introduced to the system.

This research culminated in a special provision on the application of pervious concrete as a stormwater management tool specifically for use by VDOT. The work presented in this paper supports the notion that VDOT can successfully use pervious concrete in low-volume traffic applications. With the creation of the special provision on the use of pervious concrete, VDOT will have more opportunities for effective stormwater management practices.

7.0 - Special Provision

The VDOT special provision (SP) on pervious concrete was developed based on the results of the field observations and analyses, lab work, and literature review. The full SP document is in the appendix of this report. The VDOT SP includes materials and mixture proportions, requires a minimum infiltration rate, indicates weather restrictions, mandates a pre-placement conference, provides construction process requirements, instructs on quality control, gives acceptance criteria, and dictates payment procedures.

The required minimum infiltration rate was chosen as 100 in/hr, which provides plenty of infiltration capacity for anticipated stormwater runoff volumes in Virginia and is based on findings in both the literature and also laboratory experimentation. The SP indicates a target void content of 20% which is comparable to designs currently used by private contractors in the state of Virginia. The allowable w/cm range is 0.27 to 0.35, though the work done at the VTRC lab used a w/cm of 0.33. For the fresh density, a range of 128 to 138 lb/ft^3 was selected to ensure both sufficient infiltration capabilities and satisfactory strength and durability. A minimum compressive strength of 2,000 psi at 28 days was specified. For the mix design, a range of 500 to 600 lb/yd^3 was selected for the cementitious material content. As was evident in the Results (Section 5.0), the cement content has a strong correlation with void content of a mixture. Though the basic mixture components of PC are cementitious material, water, coarse aggregate, and admixtures, the SP allows the inclusion of fine aggregate and fibers for improved strength and durability. For quality control and assurance, a trial batch and a test panel are required to be placed prior to placement of the actual lot. If the trial batch and test panel show satisfactory qualities according to the SP, placement of the actual lot can occur. The trial batch and the test panel would also indicate if the special provision values need modification to ensure satisfactory performance based on the local materials used in a specific project.

8.0 – Conclusions

This study led to the following conclusions:

- Density is related to void content; higher density leads to lower void content.
- Density is affected by the compaction effort.

- Infiltration rate and the hydraulic conductivity is related to the density of pervious concrete; higher infiltration and hydraulic conductivity is obtained with lower density.
- Void content of pervious concrete is related to the cementitious material content; lower cementitious material content yields higher void content.
- Compressive or flexural strength of pervious concrete is related to the density; higher density results in higher strength.
- Impact and abrasion resistance are related to density; higher density yields higher abrasion resistance.
- Pervious concrete requires an optimization between the conflicting infiltration capability and the strength or the abrasion resistance as these are intrinsically associated with the long term satisfactory performance of the pervious concrete.
- Clay and sand clogs pervious concrete; however, cleaning by vacuuming (or better, with power washing and vacuuming) retrieves the infiltration capabilities and the system once again functions properly within the reasonable range expected of pervious concrete after it has been clogged.
- A review of the literature in addition to the work conducted in the VTRC laboratory indicates that pervious concrete could be an effective stormwater management method if installed and cared for properly.
- A special provision is required for the implementation of pervious concrete for stormwater management in VDOT facilities and has been prepared as a result of this study.

9.0 – Recommendations and Future Work

Pervious concrete is still a relatively new technology and much about the material remains to be explored, developed, and optimized. However, a basic understanding of pervious concrete exists and with applications and practice, more will be learned. In particular, the following subjects are suggested for further research:

- Explore the impact of fine aggregates in the mix by including regular weight sand and light weight sand. In particular, an analysis of the trade-off of improved strength and durability with a possible decrease of infiltration rates would be helpful.
- Identify the influence of dispersed synthetic fibers on strength and infiltration capabilities of PC.
- Analyze pore distribution of cross-sections of pervious concrete to determine the influence of compaction methods. Compaction methods greatly effect pore distribution and void content and a better understanding of this effect would be beneficial.
- Determine if disconnected pore space that traps runoff and debris and interrupts infiltration is an issue of significant concern.
- Conduct a life cycle analysis of pervious concrete including effects of seasonal cleaning and long-term performance.
- Analyze pollutant removal efficiency of PC on runoff.
- Determine the influence of infiltration through PC pavement system on groundwater in terms of recharge and also the introduction of contaminants.

10.0 - References

ACI Committee 522. 2013. “Specification for Pervious Concrete Pavement.” ACI Standard ACI 522.1-13. American Concrete Institute.

Ahiablame, Laurent M., Bernard A. Engel, and Indrajeet Chaubey. 2012. “Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research.” *Water, Air, & Soil Pollution* 223 (7): 4253–73. doi:10.1007/s11270-012-1189-2.

Amde, A.M., and S. Rogge. 2013. “Development of High Quality Pervious Concrete Specifications for Maryland Conditions.” State Highway Administration Research Report MD-13-SP009B4F. The University of Maryland. http://www.roads.maryland.gov/OPR_Research/MD-13-SP009B4F_Pervious-Concrete-Specifications_Report.pdf.

Anderson, Ian, Mark Suozzo, and Mandar Dewoolkar. 2013. “Laboratory & Field Evaluations of Pervious Concrete.” 13–007. University of Vermont Transportation Research Center. http://www.uvm.edu/~transctr/research/trc_reports/UVM-TRC-13-007.pdf.

ASTM. 2004. “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.” C39. West Conshohocken, PA.

ASTM, 2010. “Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter”, D5084-10, ASTM International, West Conshohocken, PA.

ASTM. 2011. “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.” C496. West Conshohocken, PA.

ASTM 2014. “Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete.” C1688. ASTM International.

ASTM 2015a. “Standard Test Method for Infiltration Rate of In Place Pervious Concrete.” C1701. ASTM International.

ASTM 2015b. “Standard Test Method for Density and Void Content of Hardened Pervious Concrete.” C1754. ASTM International.

ASTM 2015c. “Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion.” C1747. ASTM International.

Caltrans. 2016. “Pervious Pavement Design Guidance.” Caltrans Storm Water Quality Handbook. California Department of Transportation. http://www.dot.ca.gov/hq/oppd/stormwtr/guidance/DG-Pervious-Pvm_052716.pdf.

Chandrappa, Anush K., and Krishna Prapoorna Biligiri. 2016. “Pervious Concrete as a Sustainable Pavement Material – Research Findings and Future Prospects: A State-of-the-Art Review.” *Construction and Building Materials* 111 (May): 262–74. doi:10.1016/j.conbuildmat.2016.02.054.

Chen, Yu, Kejin Wang, Xuhao Wang, and Wenfang Zhou. 2013. “Strength, Fracture and Fatigue of Pervious Concrete.” *Construction and Building Materials* 42 (May): 97–104. doi:10.1016/j.conbuildmat.2013.01.006.

Dong, Qiao, Hao Wu, Baoshan Huang, Xiang Shu, and Kejin Wang. 2013. “Investigation into Laboratory Abrasion Test Methods for Pervious Concrete.” *Journal of Materials in Civil Engineering* 25 (7): 886–92. doi:10.1061/(ASCE)MT.1943-5533.0000683.

EPA. 2005. “Stormwater Phase II Final Rule: Small MS4 Stormwater Program Overview. Fact Sheet 2.0.”*Office of Water: EPA 833-F-00-002.* https://www3.epa.gov/npdes/pubs/fact2-0.pdf. Accessed August 17, 2016.

EPA. 2016. “NPDES Stormwater Program.” Overviews and Factsheets. Accessed April 23, 2016. https://www.epa.gov/npdes/npdes-stormwater-program.

Haselbach, Liv M., Srinivas Valavala, and Felipe Montes. 2006. “Permeability Predictions for Sand-Clogged Portland Cement Pervious Concrete Pavement Systems.” *Journal of Environmental Management* 81 (1): 42–49. doi:10.1016/j.jenvman.2005.09.019.

Henderson, Vimy, and Susan Tighe. 2012. “Evaluation of Pervious Concrete Pavement Performance in Cold Weather Climates.” *International Journal of Pavement Engineering* 13 (3): 197–208. doi:10.1080/10298436.2011.572970.

Hershfield, David. 1961. “Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years.” Technical Paper 40. US Department of Agriculture. http://www.nws.noaa.gov/oh/hdsc/PF_documents/TechnicalPaper_No40.pdf.

Hunt, William. 2009. “Urban Waterways: Maintaining Permeable Pavements.” Cooperative Extension AG-588-23 W. NC State University College of Agriculture & Life Sciences. https://www.bae.ncsu.edu/extension/ext-publications/water/protecting/ag-588-23-maintaining-permeable-pavements.pdf.

Kevern, J., D. Biddle, and Q. Cao. 2015. “Effects of Macrosynthetic Fibers on Pervious Concrete Properties.” *Journal of Materials in Civil Engineering* 27 (9): 6014031. doi:10.1061/(ASCE)MT.1943-5533.0001213.

Kevern, J., K. Wang, M.T. Suleiman, and V.R. Schaefer. 2006. “Pervious Concrete Construction: Methods and Quality Control.” NRMCA Concrete Technology Forum. http://www.rmc-foundation.org/images/PCRC%20Files/Construction%20Techniques/Pervious%20Concrete%20Construction%20-%20Methods%20and%20Quality%20Control.pdf.

Maryland 2016. “Permeable Pavement Fact Sheet Information for Howard County, Maryland Homeowners.” University of Maryland. https://extension.umd.edu/sites/default/files/_docs/programs/mastergardeners/Howardcounty/Baywise/PermeablePavingHowardCountyMasterGardeners10_5_11%20Final.pdf.

Montes, Felipe, and Liv Haselbach. 2006. “Measuring Hydraulic Conductivity in Pervious Concrete.” *Environmental Engineering Science* 23 (6): 960–69. doi:10.1089/ees.2006.23.960.

MS19 2016. “MS19 Plan Checklist.pdf.” Accessed May 26. https://www.vbgov.com/government/departments/planning/DSC/Documents/MS19%20Plan%20Checklist.pdf.

Munoz, Armando. 2012. “Evaluation of Sustainability, Durability and the Effect of Specimen Type in Pervious Concrete Mixtures.” Master of Science, Texas State University - San Marcos. https://digital.library.txstate.edu/bitstream/handle/10877/4280/MARINES-MUNOZ-THESIS.pdf?sequence=1.

NJ DOT. 2004. “Chapter 9.7: Standard for Pervious Paving System.” In *New Jersey Stormwater Best Management Practices Manual*.

NRCS 2016. “Soil Survey Technical Note 6 | NRCS Soils.” Accessed June 10, 2016. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_053573.

NRMCA. 2004. “Pervious Concrete.” CIP-38. Concrete in Practice. National Ready Mixed Concrete Association.

NRMCA. 2016. “NRMCA | Pervious Concrete Contractor Certification Program.” Accessed June 2, 2016. http://www.nrmca.org/education/certifications/pervious_contractor.htm.

NRMCA. 2015. “Pervious Concrete Pavement Maintenance and Operations Guide.”

Percoa 2016. “Percoa, LLC - Home.” Accessed June 21, 2016. http://www.percoausa.com/.

Putman, Bradley J., and Andrew I. Neptune. 2011. “Comparison of Test Specimen Preparation Techniques for Pervious Concrete Pavements.” *Construction and Building Materials* 25 (8): 3480–85. doi:10.1016/j.conbuildmat.2011.03.039.

Qin, Yinghong, Haifeng Yang, Zhiheng Deng, Jiang He, Yinghong Qin, Haifeng Yang, Zhiheng Deng, and Jiang He. 2015. “Water Permeability of Pervious Concrete Is Dependent on the Applied Pressure and Testing Methods, Water Permeability of Pervious Concrete Is Dependent on the Applied Pressure and Testing Methods.” *Advances in Materials Science and Engineering, Advances in Materials Science and Engineering* 2015, 2015 (January): e404136. doi:10.1155/2015/404136, 10.1155/2015/404136.

Schwartz, S. 2010. “Effective Curve Number and Hydrologic Design of Pervious Concrete Storm-Water Systems.” *Journal of Hydrologic Engineering* 15 (6): 465–74. doi:10.1061/(ASCE)HE.1943-5584.0000140.

Smith, David R., Kevin Earley, and Justin M. Lia. 2012. “Potential Application of ASTM C1701 for Evaluating Surface Infiltration of Permeable Interlocking Concrete Pavements.” In *Pervious Concrete*, by Matthew Offenberg, edited by Heather J. Brown, 1–9. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International. http://www.astm.org/doiLink.cgi?STP104560.

Stormcrete 2016. “StormcreteTM: Precast Porous Concrete.” 2016. Accessed June 9. http://storm-crete.com/product.html.

The Concrete Producer 2015. “Precast Pervious Concrete.” *TheConcreteProducer*. Accessed June 6, 2016. http://www.theconcreteproducer.com/precast-and-prestressed-concrete/precast-pervious-concrete_o.aspx.

Thakre, Nalini, Hirendra Rajput, Jaya Saxena, and Harish Mitangale. 2014. “Comparative Study on Strength and Permeability of Pervious Concrete by Using Nylong and Polypropylene Fiber.” *International Journal of Computing and Technology* 1 (4). http://www.ijcat.org/IJCAT-2014/1-4/Comparative-Study-on-Strength-and-Permeability-of-Pervious-Concrete%20by-Using-Nylon-and-Polypropylene-Fiber.pdf.

US Climate 2016. “Climate Virginia - Temperature, Rainfall and Average.” Accessed May 9. http://www.usclimatedata.com/climate/virginia/united-states/3216.

USDOC, US Department of Commerce: National Oceanic and Atmospheric Administration. 2016. “NOAA’s National Ocean Service Education: Nonpoint Source Pollution.” Accessed May 23. http://oceanservice.noaa.gov/education/kits/pollution/04 nonpointsource.html.

USDA: Natural Resources Conservation Service Virginia. 2016 “Chesapeake Bay and Virginia.” http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/va/home/?cid=nrcs142p2_018880. Accessed August 17, 2016.

VAAA 2016. “Virginia Asphalt Association.” 2016. Accessed May 27. http://www.vaasphalt.org/facts-about-virginias-asphalt/.

VADEQ 2013a. “Permeable Pavement.” VA DEQ Stormwater Design Specification 7. http://chesapeakestormwater.net/wp-content/uploads/downloads/2014/04/VA-BMP-Spec-No-7-PERMEABLE-PAVEMENT-FINAL-DRAFT-EDITS-v2-0-02April2014.pdf. Accessed August 17, 2016.

VADEQ 2013b. “Chapter 10: Uniform Stormwater BMP Sizing Criteria.” Virginia Stormwater Management Handbook. http://www.deq.virginia.gov/fileshare/wps/ 2013_SWM_Handbook/

VADEQ 2016a. “Stormwater.” Accessed May 24. http://www.deq.virginia.gov/Programs/Water/StormwaterManagement.aspx.

VADEQ 2016b. “Nonpoint Source Pollution.” 2016. Accessed May 24. http://www.deq.virginia.gov/Programs/Water/WaterQualityInformationTMDLs/NonpointSourcePollutionManagement/NonpointSourcePollution.aspx.

VADEQ 2016c. “ESC Basic Module 3.” Accessed May 25, 2016. http://www.deq.virginia.gov/Portals/0/DEQ/ConnectwithDEQ/Training/ESC/ESC_Basic_Module3_V2.pdf.

VDOT 2013. “2013 Visitation Data for the VDOT Statewide Safety Rest Areas/Welcome Center Program.” VDOT.http://www.virginiadot.org/info/resources/2013_Average_Visitors.pdf.

VDOT 2015.“Permeable Pavement.” Special Provision. VDOT.

VDOT. 2016. “Park and Ride in Virginia.” 2016. Accessed June 22. http://www.virginiadot.org/travel/parkride/home.asp.

“Virginia Stormwater BMP Clearinghouse - BMP Standards and Specifications.” 2016. Accessed May 24. http://www.vwrrc.vt.edu/swc/StandardsSpecs.html.

VWRRC. 2016a. “Post-Construction BMP’s.” . Accessed May 24. http://www.vwrrc.vt.edu/swc/PostConstructionBMPs.html.

VWRRC. 2016b. “Non-Proprietary BMPs.” 2016. Accessed May 24. http://www.vwrrc.vt.edu/swc/NonProprietaryBMPs.html.

VWRRC 2016c. “Virginia Stormwater BMP Clearinghouse - Regulatory Programs.” Accessed June 16 2016. http://www.vwrrc.vt.edu/swc/RegulatoryPrograms.html.

VWRRC 2016d. “Proprietary BMPs.”Accessed June 17, 2016. http://www.vwrrc.vt.edu/swc/ProprietaryBMPs.html.

Wang, K., V.R. Schaefer, J Kevern, and M.T. Suleiman. 2006. “Development of Mix Proportion for Functional and Durable Pervious Concrete.” NRMCA Concrete Technology Forum: Focus on Pervious Concrete. Nashville, TN: NRMCA.

Winston, Ryan, Jay Dorsey, William Hunt. 2016. “Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio.” *Science of the Total Environment* (553): 83-95.

WisDOT. 2012. “Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost.” Transportation Synthesis Report. Wisconsin Department of Transportation.

Appendix

A.1 Special Provision

VIRGINIA DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION FOR

PERVIOUS CONCRETE FOR PARKING LOTS

April 13, 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, and field testing agency. In this conference, materials, personnel qualifications, concrete production, preparation, placing, curing, and testing procedures will be discussed. Before work proceeds, the Engineer's approval shall be obtained for any issues that deviate from this special provision.

V. PERVIOUS CONCRETE PAVEMENT CONSTRUCTION

1. **Thickness:** The 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 ± 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 Contract. 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.

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.

E. Compressive strength from cores (minimum 2,000 psi at 28 days) (ASTM C39). Cores shall be 4 inches in diameter. Core holes shall be filled with A3 concrete or an approved patching material.

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. Core holes shall be filled with A3 concrete.

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 and length of core, it will be subject to rejection, removal, and replacement at Contractor's expense.

VIII. MEASUREMENT AND PAYMENT

Installation costs for pervious concrete shall be paid on a per square yard basis. 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