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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

DEVELOPMENT OF HIGH QUALITY PERVIOUS CONCRETE SPECIFICATIONS FOR MARYLAND CONDITIONS

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THE UNIVERSITY OF MARYLAND

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16. Abstract

One of the main objectives of this research was to develop preliminary specifications for high quality pervious concrete suitable for use in Maryland State Highway Administration (SHA) projects. The study utilized aggregates that are used in SHA projects and the durability studies that were conducted assumed Maryland weather conditions. Investigations were conducted to enhance the structural and durability characteristics of pervious concrete through the use of different admixtures. The admixtures included cellulose fibers, a delayed set modifier and a viscosity modifier. Pervious concrete specimens were tested for density, void content, compressive strength, split tensile strength, permeability, freeze-thaw durability, and abrasion resistance. Three different types of freeze-thaw durability tests were conducted to mimic potential field conditions including the possibility of clogged pavement. The freeze-thaw durability tests included: fully saturated tests, 50% saturated tests, and 0% saturated dry hard freeze tests.

The study found that of the different admixtures tested, cellulose fibers had the largest impact in improving durability. Including cellulose fibers in the pervious concrete mix resulted in significant increases in resistance in all three freeze-thaw durability tests. It also resulted in significant increases in abrasion resistance. By bridging the gap between the coarse aggregates, the cellulose fibers bound the pervious concrete mixture with an interwoven matrix of fibers. This also improved the tensile strength of the pervious concrete. The delayed set modifier resulted in a more fluid mix and in large gains in compressive strength at seven and fourteen days. This admixture may inhibit some of the cement from setting around aggregates and may result in some cement settling to the bottom and forming a less pervious layer. The viscosity modifying admixture created a more workable and easier to mold mix. Its effect on strength and durability were minimal.

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ABSTRACT

Development of High Quality Pervious Concrete Specifications for Maryland Conditions

One of the main objectives of this research was to develop preliminary specifications for high quality pervious concrete suitable for use in Maryland State Highway Administration (SHA) projects. The study utilized aggregates that are used in SHA projects, and the durability studies were conducted assuming Maryland weather conditions. Investigations were conducted to enhance the structural and durability characteristics of pervious concrete through the use of different admixtures. The admixtures included cellulose fibers, a delayed set modifier and a viscosity modifier. Pervious concrete specimens were tested for density, void content, compressive strength, split tensile strength, permeability, freeze-thaw durability, and abrasion resistance. Three different types of freeze-thaw durability tests were conducted to mimic potential field conditions, typical to Maryland, and including the possibility of clogged pavements. The freeze-thaw durability tests included: fully saturated tests, 50% saturated tests, and 0% saturated dry hard freeze tests.

The study found that of the different admixtures tested, cellulose fibers had the largest impact in improving durability. Including cellulose fibers in the pervious concrete mix resulted in significant increases in resistance in all three freeze-thaw durability tests. It also resulted in significant increases in abrasion resistance. By bridging the gap between the coarse aggregates, the cellulose fibers bound the pervious concrete mixture with an interwoven matrix of fibers. This also improved the tensile strength of the pervious concrete. The delayed set modifier resulted in a more fluid mix and large gains in compressive strength at seven and fourteen days. This admixture may inhibit some of the cement from setting around aggregates and may result in some cement settling to the bottom and forming a less pervious layer. The viscosity modifying admixture created a more workable and easier to mold mix. Its effect on strength and durability were minimal.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter One

Introduction

1.1 Background

Portland cement pervious concrete (PCPC) is gaining a lot of attention. Various environmental benefits such as controlling stormwater runoff, restoring groundwater supplies, and reducing water and soil pollution have become focal points in many jurisdictions across the United States (Kajio et al 1998). Portland cement pervious concrete is a discontinuous mixture of coarse aggregate, hydraulic cement and other cementitious materials, admixtures and water. By creating a permeable surface, stormwater is given access to filter through the pavement and underlying soil, provided that the underlying soil is suitable for drainage. This allows for potential filtration of pollutants. To achieve this permeability, PCPC is typically designed with high void content (15-25%). The U.S. EPA has published a Porous Pavement fact sheet (US EPA 1999) that lists the advantages of pervious pavements. These advantages are:

- Water treatment by pollutant removal;
- Less need for curbing and storm sewers;
- Improved road safety because of better skid resistance; and
- Recharge to local aquifers.

While it is seen as a new and emerging application, pervious concrete does have its disadvantages. Poor performances in cold regions, arid regions, regions with high wind erosion rates, and areas of sole-source aquifers have shown the downside of using pervious concrete (Pratt 1997). In addition, the use of porous concrete is highly constrained, requiring deep permeable soils, restricted traffic, and adjacent land uses. Although PCPC has seen an increase in application in recent years, there is still limited experience with the material. According to the EPA, approximately 75 percent of pervious concrete pavements have failed. This has been attributed to poor design, inadequate construction techniques, low permeability soil, heavy vehicular traffic, and poor maintenance (US EPA 1999). Failure has been determined by the EPA as a pervious pavement that can no longer function as a stormwater retention material due to clogging and/or structural failure. Prior to wide use of pervious concrete in Maryland, it is important to study the effect of Maryland weather conditions with regional materials used in standard State Highway Administration (SHA) projects.

1.2 Problem Statement

The porosity of pervious pavements is provided by omitting all or most of the fine aggregates which impart the necessary percolation characteristics to the concrete. In 2001 the American Concrete Institute (ACI) formed committee 522, "Pervious Concrete", to develop and maintain standards for the design, construction, maintenance, and rehabilitation of pervious concrete. This recent interest in porous surfaces as a substitution for impervious surfaces can be attributed to desirable benefits such as stormwater retention, which includes stormwater treatment. Because of the high void content PCPC generally has low strength (800-3000 psi) which limits applications in cold weather regions and is responsible for various distresses and pavement failures. The need to develop a high performing pervious concrete specification for Maryland conditions was the basis of this report. Several admixtures were tested along with regional materials often used in SHA projects. Structural and durability characteristics were measured against a control mix.

Investigation of pervious concrete performance under cold weather conditions has been studied. Iowa and Minnesota have each funded various projects on pervious concrete in cold weather regions. However, these states do not have the cyclic freezing and thawing that occurs in Maryland.

Currently, Maryland has not fully adopted a pervious concrete specification but has been gathering various researches on the subject and has developed a draft specification based on the ACI 522 Specification. While numerous states have created such a document, the unique weather conditions in Maryland in combination with Maryland materials have not been evaluated and tested. Several admixtures in conjunction with typical aggregates found in Maryland state projects were included in the design mixtures for this project. Structural and durability tests are needed before a preliminary specification can be developed for pervious concrete based on materials indigenous to Maryland and suitable for Maryland climatic conditions.

1.3 Scope of Work

The present study was conducted to investigate pervious concrete made from aggregates used in Maryland State projects under Maryland weather conditions. In this study, several admixtures were used and the pervious concrete specimens were tested for density and void content, compressive strength, split tensile strength, permeability, freeze-thaw capacity, and abrasion resistance. Testing was performed at the University of Maryland College Park campus and Eastern Testing and Inspection Laboratory (ETI) located in Frederick, Maryland.

1.4 Outline of Report

This report is divided into six chapters, including this introduction. Chapter 1 outlines the scope of work. Chapter 2 provides the literature review from both national and international sources. Description and discussion of the different mix designs are included in Chapter 3. Chapter 4 addresses the procedures for each of the six tests. Chapter 5 discusses the results and Chapter 6 provides summary and conclusions.

Chapter Two
Background Information

2.1 Introduction

Sustainable construction designs have become extremely popular within the last few years. Reducing the strain on our environment is essential to the overall health and wellbeing of our society. While a variety of new designs and technologies have transpired from this green movement, one of the more profound impacts has been in the area of stormwater management (SWM). Named one of the best management practices for SWM quality, pervious concrete has the ability to capture the runoff of rainwater and remove trace pollutants (NRMCA 2004). While pervious concrete has been around for many years, it has seen a significant increase in interest in recent years with the adoption of the federal clean water legislation. One of its first uses was in southern Georgia where the preservation of the natural ecosystem played an important role in selecting pervious concrete (Ferguson 2005). Since then, other states such as Florida, New Mexico, Utah, California, Oklahoma, Illinois, and Wisconsin have implemented pervious concrete designs (Mathis 1990).

Pervious concrete can be defined as an open graded or “no-fines” concrete that allows rain water to percolate through to the underlying sub-base (ACI Committee 522 2006). The principal ingredients are quite similar to conventional concrete: aggregate, Portland cement, admixtures, fine aggregate (optional), and water. The main difference is the percentage of void space within pervious concrete. Typical ranges of void space are between 15-25 percent or roughly .08 in to .32 in (2 mm to 8 mm) (NRMCA 2004). To create a pervious concrete pavement, the pervious concrete (ranging from 4 to 8 inches in thickness) is placed on top of an aggregate base. The thickness of this aggregate base is dependent on a number of influencing factors. A filter fabric can be placed to separate the underlying soil from the pervious concrete (see Figure 2.1). This allows the impediment of the soil from percolating or penetrating up and clogging the pores of the concrete (Tennis et al 2004). The use of sub-base material is dependent on soil conditions as well as the intended application.

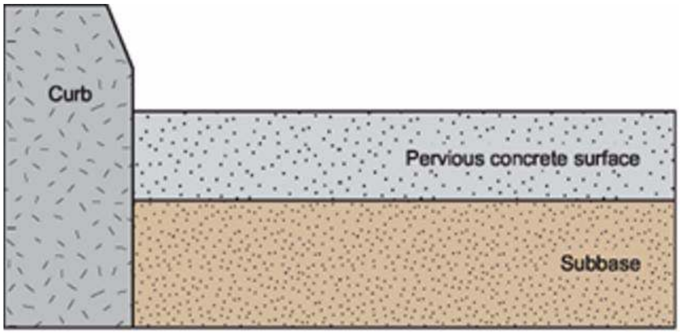
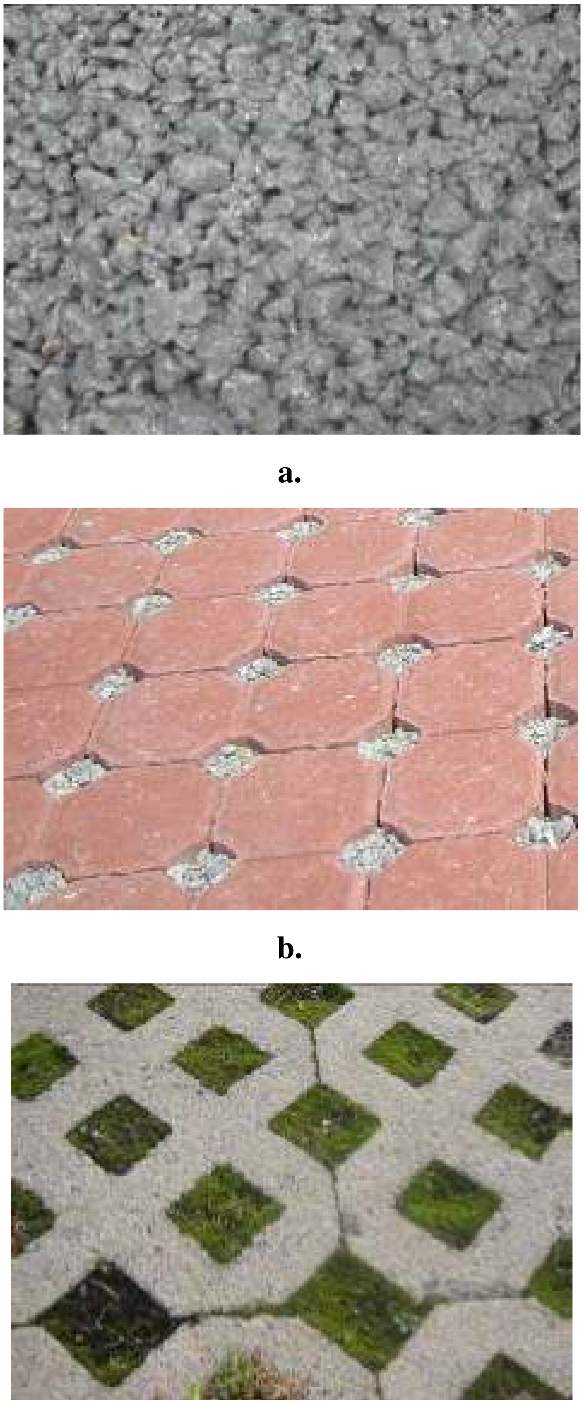


Figure 2.1: Section of a Typical Pervious Concrete Pavement

2.1.1 Types of Pervious Pavements

There are several types of pervious pavements that are used in practice. The three common types as shown in Figure 2.2 are pervious concrete, pervious interlocking concrete pavers, and concrete grid pavers (Collins et al 2008 and Bean et al 2007).



a.

b.

c.

Figure 2.2: Types of Pervious Pavements a. Pervious Concrete, b. Pervious Interlocking Concrete Pavers, c. Concrete Grid Pavers

2.1.2 Detention and Retention Designs

While the key element in designing any pervious concrete pavement is the limitation of stormwater runoff, pervious concrete pavements may be classified as either detention design or a retention design. To be classified as a detention pervious pavement, the design must detain the stormwater until it is discharged into the drainage network. To be classified as a retention pervious pavement, the design must not only hold the stormwater but also retain and treat until infiltration can occur into the underlying soil. The retention system is heavily dependent on the underling soil properties. A subsurface with low permeability (i.e. clay) may not be able to effectively drain the water prior to the next storm event. If this should occur, saturation and percolation up through the pervious concrete could be imminent (Tyner et al 2009).

For the retention system, the ability to treat the stormwater is extremely beneficial. Two types of treatment can occur: mechanical and biological (Schaefer et al 2006). For a mechanical treatment, the particles are trapped on the concrete surface. For a biological treatment, the particles are degraded on the concrete surface or at the sub-base level. A mechanical treatment was tested by Pratt et al (1990) to determine the effect pervious concrete had with entrapping motor oil. By placing a small amount of motor oil on a one square foot specimen and simulating three rainfalls, he was able to determine that the pervious concrete was able to retain 99.6% of the motor oil. Biological treatment processes were also evaluated (Pratt et al 1990). Microorganisms were applied to the samples as well as a slow release of fertilizer. Oil was applied to the samples. Runoff was then collected and measured for oil concentrations. It was found that the effluent contained negligible amount of oil concentration.

2.1.3 Passive or Active Mitigation Systems

Pervious concrete pavement can not only handle the surface area runoff from the pavement, it can also be designed to handle surrounding runoff. Local jurisdictions often require the pervious pavement to handle not only the given footprint of the pervious pavement area but also require the drainage of runoff from buildings, construction areas, etc. The latter case has been deemed as an active mitigation system for pervious concrete pavements while the former has been classified as passive (NRMCA 2004).

A passive mitigation system essentially reduces the quantity of impervious surfaces by replacing it with a permeable one. The design is limited to only capturing and handling the amount of rainwater over the surface area, not taking into account the surrounding topography, buildings, site, or other non-permeable areas (NRMCA 2004).

An active mitigation system on the other hand, is just the opposite. Certain jurisdictions may require the use of pervious concrete to handle stormwater under its own footprint as well as handle a considerable portion of runoff from other areas. Those other areas might include buildings, adjacent impervious surfaces including delivery areas, dumpster areas, heavy traffic areas, traffic islands, and buffer zones. By incorporating all of these areas into the design, the active mitigation system can minimize the overall footprint of the developed site.

2.2 Material Properties

2.2.1 Aggregate

The standard type aggregate for use in pervious concrete is typically crushed stone or river gravel. Typical sizes are from 3/8 in. to 1 in. (Tennis et al 2004). Fine aggregates are either used sparingly or removed altogether from the mix design. It has been shown that using smaller aggregates increases the compressive strength of pervious concrete by providing a tighter bond between coarse aggregate and cement. Using fine aggregates in the mix design of pervious concrete will also decrease the void space (Tennis et al 2004). Increasing the percent amount of larger aggregates will increase the void ratio in pervious concrete, but will decrease the compressive strength (Crouch 2007).

Using recycled aggregates has also been researched. Four mix designs were studied using 15%, 30%, 50%, and 100% recycled aggregates and compared to the virgin pervious concrete samples. It was found that samples containing 15% or less recycled aggregates exhibited almost identical characteristic to the virgin sample (Rizvi et al 2010).

The size of the aggregate also has an important role in pervious concrete. While a 3/4 in. aggregate size allows for greater void space, a 3/8 in. aggregate improves the workability (Flores et al 2007). The use of 3/4 in. aggregate can decrease settling and workability. Recent studies have also found that pervious concrete with smaller aggregates had higher compressive strength (Yang et al 2003). It was noted that the smaller aggregate sizes allowed for more cementitious material to bind around the aggregate and hence allowed for greater contact between the aggregate/binder.

2.2.2 Fine Particles

While pervious concrete is considered a "no fines" concrete, a small percentage of fine particles can be added to increase the compressive strength of the pervious concrete mix. The inclusion of fine particles has a direct correlation to the paste/mortar strength. Providing a thicker paste layer around the coarse aggregates results in improved compressive strength (Schaefer et al 2009). As seen in Figure 2.3, there is a significant relationship between compressive strength and sand to gravel ratio. When the sand to gravel ratio is increased to 8 %, the mortar bulks up and increases the strength. When the sand to gravel ratio increases beyond the 8 % mark, the 7 day compressive strength begins to fall (Schaefer et al 2009).

Both Europe and Japan have been using smaller aggregates as well as the inclusion of sand for their mix design (Kajio et al 1998 and Beeldens et al 2003). An optimization of 10%-20% of fine sand to coarse aggregate has been shown to increase compressive strength from ~2000 pounds per square inch (psi) to ~2700 psi (Meininger 1988). A slight decrease in permeability correlates to the increase in fine particles.

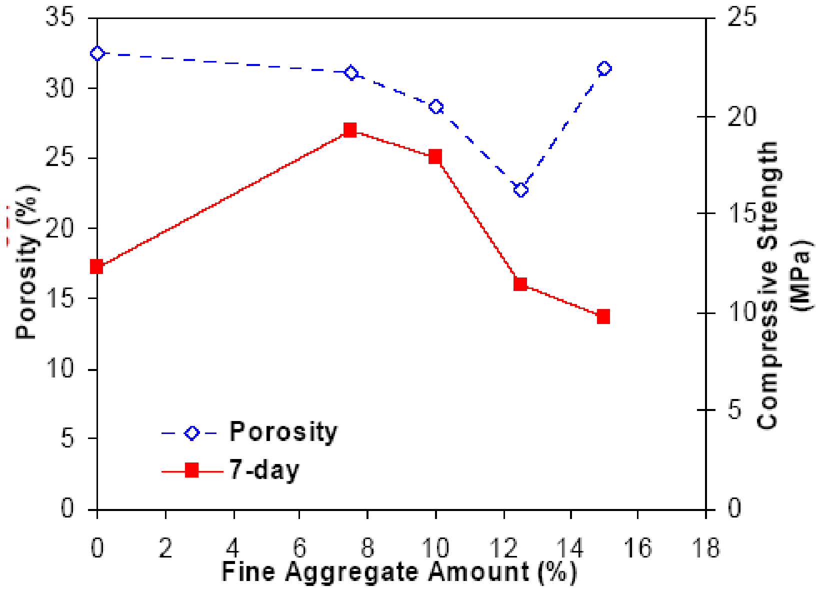
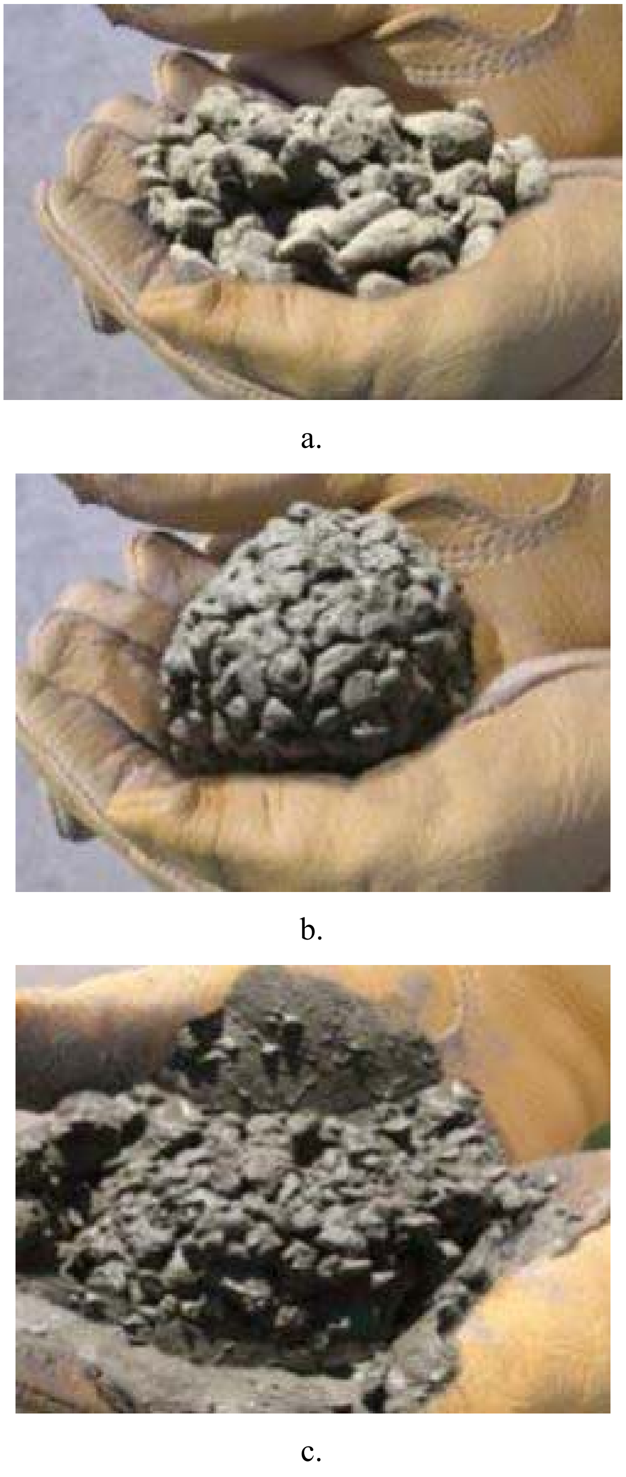


Figure 2.3: Relationships between Fine Aggregate and Porosity/Compressive Strength

2.2.3 Cementitious Materials

Portland Type I or II conforming to ASTM C150 or Type IP, IS conforming to ASTM C-595 have been used as the binder for the aggregates (ACI Committee 522 2006). Additional materials that can be used in the cementitious mix are silica fume, fly ash, and slag cement (ACI Committee 522 2006 and Tennis et al 2004).

While any potable water can be used for mixing, the amount of water is critical for the formation of the voids in pervious concrete. Water-to-cement ratios can range from 0.27 to 0.30 with ratios as high as 0.40. Careful control of water is critical. A mix design with little water can create a very weak binder. This will create a very dry mix that is susceptible to spalling and crumbling. A mix design with too much water can collapse the void space, making an almost impenetrable concrete surface (NRMCA 2004). As seen in Figure 2.4, the specimen in Figure 2.4a has too little water, the specimen in Figure 2. 4b has the correct amount of water, and the specimen in Figure 2.4c has too much water.



a.

b.

c.

Figure 2.4: Pervious Concrete With a. Too little Water, b. Appropriate Amount of Water, c. Too much Water

A study done by Meininger (1998) demonstrated the relationship between compressive strength and water-to-cement ratio (see Figure 2.5). The optimal w/c ratio with the highest compressive strength was found to be between 0.3 and 0.35. Lower w/c ratios provide poor cohesion between the aggregates. Higher w/c ratios reduce the tensile capacity by the introduction of capillary pores.

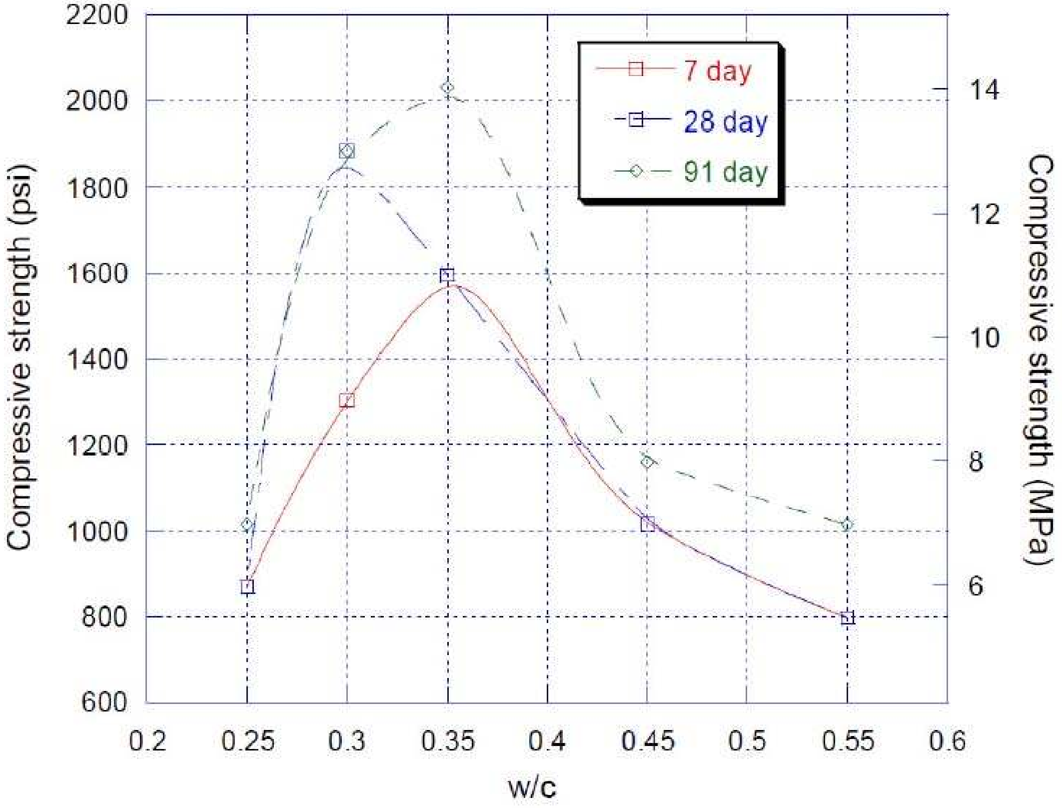


Figure 2.5: Relationship between Water-to-Cement and Compressive Strength

Another study by Chindaprasirt, Hatanaka, Chareerat, Mishima, and Yuasa (2008) determined that water-to-cement ratio has a direct correlation to cement paste characteristics, and mixing time of the porous concrete. It was noted that keeping a relatively low water-to-cement ratio, around 0.2 to 0.3, maintains the continuity of the paste layer with coarse aggregate. This also aids in the texture and workability of the pervious concrete. By achieving an even thickness of the paste (150-230 mm) within the porous concrete mix, this can achieve suitable void ratios of 15-25% and strengths ranges from 3190 psi to 5656 psi (22-39 MPA).

2.2.4 Admixtures

The use of admixtures in conventional concrete is essential and vital to performance and workability. High-range water-reducing (HRWR) admixtures are applied to concrete mixes to affect the set time of concrete (NRMCA 2004). They require less water and increase the slump of concrete. Caution must be used when applying HRWR to pervious concrete. Large dosage can cause the cement to segregate from the aggregate and settle at the bottom of the concrete, forming an impervious layer of cement (Flores et al 2005).

Latex, a styrene butadiene rubber material which has been used to improve the cement-aggregate bond (Ramakrishnan 1992), was used to replace a certain amount of Portland cement to determine its potential application in pervious concrete pavements (Wang et al 2006). Approximately 10% of Portland cement was replaced with Latex and it was found that pervious concrete specimens with Latex had, on average, a lower compressive strength. Although the use of Latex lowered the compressive strength, the specimens showed an increase in tensile strength, indicating an improved resistance to cracking.

The uses of hydration controlling admixtures (HCA) were beneficial by slowing down the rate of hydration. This extended the time before the fresh concrete started to set, thereby allowing more time to form and finish the concrete surface. Using 5 fl oz/cwt of the HCA allowed 60 to 90 minutes of added working time (Bury et al 2006).

Viscosity Modifying Admixtures (VMA) may also play a pivotal role on the performance of pervious concrete. While little has been researched about the use of viscosity modifiers, the small amount of research has shown that VMA's can increase flow of concrete as well as provide ease of compaction and placement. While different VMA's can have differing effects on the overall result of pervious concrete, special attention is needed to determine and verify the correct type and amount prior to installation (Bury et al 2006).

2.2.5 Void Ratio

Percentage of voids in a sample of pervious concrete can vary significantly. The amount of void space is dependent on the amount of water needing to permeate through to the sub-base. Zouahi et al (2000) compared the relationship between percentage of voids in pervious concrete and compressive strength. Not surprisingly, he found there was an inverse proportion of compressive strength to void ratio. Generally, pervious concrete will have a void ratio between 15%-30% with an average of 20%. This accommodates both the structural requirements and the hydrological requirements of the design (Tennis et al 2004).

Two testing methods, ASTM D 7063 and ASTM C 140, can be used to test void ratio or porosity of the pervious concrete specimen. While both methods are acceptable, ASTM D 7063 can be used to determine the storage capacity of the pervious pavement. By determining the densities with the use of the displaced water method, the fractional number of voids can be used to determine the amount of water that can be accessed by the voids in the concrete (Mata 2008).

A lower void ratio increases the potential for clogging. Joung and Grasley (2008) devised a test to clog the pervious concrete specimen and measure the permeability. The clogging procedure applied 50 g of sand and 1 kg of water and thoroughly mixed the two together. The fluid like material was then poured over the pervious concrete samples. They were then flushed with clear water. This procedure was repeated five times. The specimens were then placed in a falling-head permeameter and the permeability was measured. It was found that a void ratio of 33% or greater was not affected by clogging. Specimens from 21%-31% showed increased clogging and a decrease in permeability.

While laboratory tests revealed clogging to be a factor with limited void ratios, the EPA has listed clogging as one of the primary methods of failure for pervious concrete pavements (US EPA 1999). The Florida Concrete and Products Association has reported successful removal of clogged pores from pervious pavements in service. Careful inspection, power washing, and vacuuming/sweeping of loose debris help maintain the quality and permeability of the pervious concrete system. It has been reported that much of the potential clogging material in Florida is primarily made up of sand (Mata 2008).

2.3 Permeability

2.3.1 Concrete

The ability of the concrete to drain runoff water is the key to the success of pervious concrete. Interconnected voids within the concrete allow the water to penetrate to the sub-base and remove trace contaminants (Tennis et al 2004). While there is an inverse relationship between porosity and compressive strength, it is imperative that proper pervious concrete pavement designs allow for full saturation of the sub-base and not allow the runoff water to pond within the concrete layer or above the surface (NRMCA 2004).

While there is no set standard for testing the permeability of concrete, Flores, Martinez, and Uribe (2007) have devised a testing procedure that evaluates the filtration ability of pervious concrete cores. The test involves measuring the time it takes for a given amount of water to pass from the top of a 4 x 8 inch cylinder to the bottom. To account for bi-directional flow, the pervious concrete cylinder was wrapped in a waterproof, non-absorbent material.

Another method developed to measure the permeability of pervious concrete has been the use of the falling head permeameter (Schaefer et al 2006). Figure 2.6 shows a schematic diagram of the falling head permeameter. The pervious concrete cores are encased in an impermeable, non-absorbing membrane and connected to a vertical PVC pipe with open ends on each side, labeled upstream and downstream. To remove the air voids in the pervious concrete, water was filled in the downstream end up until water reached the top of the concrete core. Water was then filled on the upstream end. Equilibrium was allowed to be reached. Water was then added to the upstream side to a height of 12 in., and fall to about 4 in. The time for the water to drop a predetermined height was recorded.

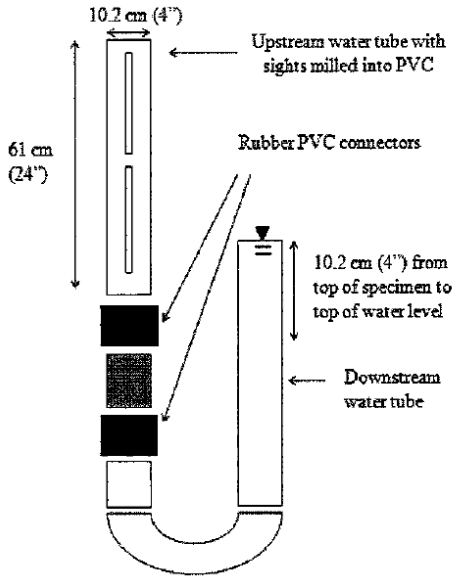


Figure 2.6: Falling Head Permeameter

2.3.2 Sub-base

Once the groundwater has percolated through the pervious concrete, the sub-base then needs to filter and infiltrate the stormwater. The size, depth, and type of sub-base material are just as important in reducing stormwater runoff as pervious concrete. The sub-base beds should have a total volume to capture and store runoff water generated by a storm in a 24 hr period (Kwiatkowski et al 2007). Undisturbed and uncompacted soil should be the foundation for the sub-base material. Applying compaction to the soil, even inadvertent compaction due to construction equipment, can have major implications on drainage. By compacting the soil, the natural voids within the underlying soil will be tightened and filtration rate will decrease.

While the thickness and stone base can play a significant role in the permeability, Tyner, Wright, and Dobbs (2009) explored the different types of treatment for pervious concrete sub-base as it relates to increased infiltration. Three different types of sub-base soil treatment were tested: 1. trenched soil and backfilled with stone aggregate, 2. ripped soil, and 3. boreholes backfilled with sand. A controlled sub-base with no treatment was also put in place and analyzed. The plots were then fully saturated and infiltration was measured. It was determined that the use of treatments greatly influenced the infiltration rate with the trenched treatment having the highest rate (25.8 cm/d) followed by ripped treatment (10.0 cm/d) and then boreholes (4.6 cm/d) (Tyner et al 2009).

It is important to try to maintain a flat ground level for pervious concrete pavements. If the slope is too steep, the runoff might collect and exit at the low point of the pavement. Ponding could occur if the collected stormwater is greater than the filtration rate (see Figure 2.7)

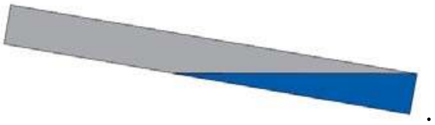


Figure 2.7: Ponding of Water to Occur on Sloped Pavements

To prevent ponding, it is recommended that the pavement should not exceed a 5% slope without implementing additional infiltration assistance. Impervious barriers will be required beneath the sub-base material to prevent the flow of water downhill (NRMCA 2004). Utilizing additional means of helping the sloped pervious pavement drain more effectively, slopes of up to 16% have been achieved (CCPC 2003). One such method involved using trenches filled with stone (see Figure 2.8).

Figure 2.8: Sloped Pervious Concrete Pavement with Dug Trenches Filled with Stone

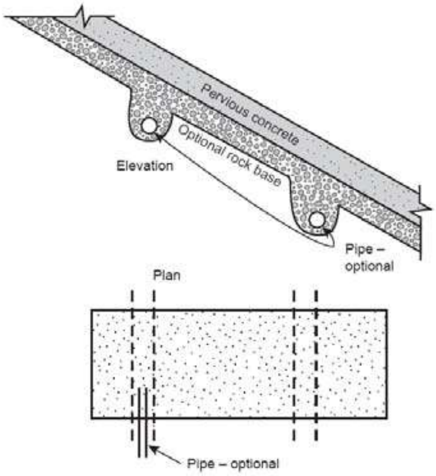


Figure 2.9: Structural Plan and Elevation of a Sloped Pervious Concrete Pavement Design

The trenches are dug across the slope, perpendicular to the pavement. A perimeter drain usually constructed of PVC pipe is installed at the bottom of the trench and then filled with washed stone. The depth and spacing of the trenches are often dictated by the slope of the pavement, the soil infiltration rate, and the maximum rainfall intensity for the site (NRMCA 2004).

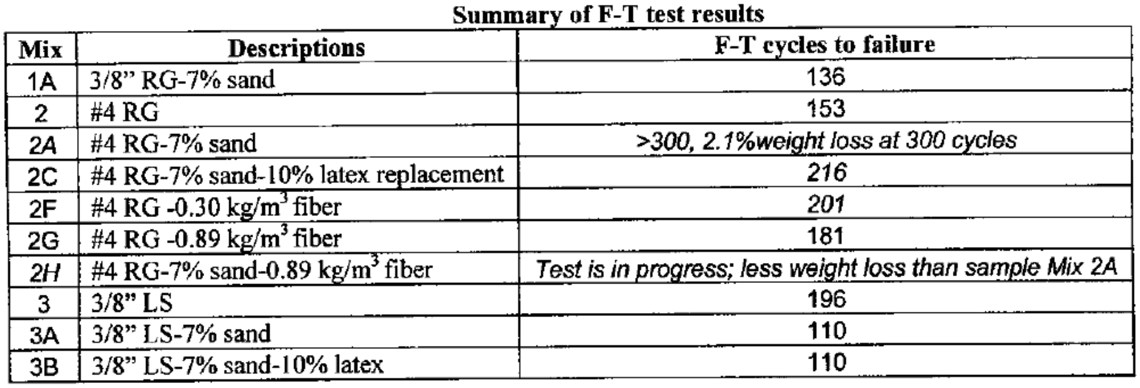
2.4 Durability

2.4.1 Freeze-Thaw Resistance

The open voided structure of pervious concrete pavements allows for the free transfer of moisture and stormwater through the pavement and into the sub-base. However, if clogging of the pores was to impede the free flow of water, this could cause water to potentially freeze and expand within the pervious concrete strata (Tennis et al 2004). Since a very thin layer of paste surrounds the aggregate, the expansive nature of freezing cycles could unbond and crack the paste from the aggregate (Yang et al 2006). Therefore, proper design for saturation and drainage from the pervious concrete surface is critical. Removal of clogged pores and annual cleaning is also recommended to ensure adequate drainage during yearly rainfall events (Tennis et al 2004).

While it has been documented that ASTM C666 may not be applicable to simulate the exact freeze-thaw conditions pervious concrete will experience in the field, it has been accepted that this test can be considered an extreme measurement for pervious concrete pavements (Wang et al 2006). Utilizing ASTM C666 for freeze-thaw testing, 10 different samples each varying in mixtures were analyzed and found that river gravel aggregates passing thru #4 sieve with 7% fine particles (sand) and 1.5 lbs/cy of fibers produced the highest resistance (see Table 2.1).

Table 2.1: Results from Freeze-Thaw Testing on River Gravel and Limestone



Summary of F-T test results

Mix	Descriptions	F-T cycles to failure
1A	3/8" RG-7% sand	136
2	#4 RG	153
2A	#4 RG-7% sand	*>300, 2.1%weight loss at 300 cycles*
2C	#4 RG-7% sand-10% latex replacement	*216*
2F	#4 RG -0.30 kg/m^3 fiber	*201*
2G	#4 RG -0.89 kg/m^3 fiber	181
2H	#4 RG-7% sand-0.89 kg/m^3 fiber	*Test is in progress; less weight loss than sample Mix 2A*
3	3/8" LS	196
3A	3/8" LS-7% sand	110
3B	3/8" LS-7% sand-10% latex	110

While average temperatures vary significantly and freeze-thaw cycles can be quite different depending on the geographic location within the continental United States, the National Ready Mixed Concrete Association (NRMCA 2004) has categorized three different types of freezing-thawing that can occur.

Dry Freeze/Hard Dry Freeze: Those areas of the country that undergo a number of freeze-thaw cycles (15+) but experience little to no precipitation during the cold months. Recommendations: A 4 to 8 inch thick sub-base of washed and cleaned aggregate below the pervious concrete pavement to allow for additional storage of water.

Wet Freeze: is defined as those areas of the country that undergo 15+ freeze-thaw cycles and experience a moderate amount of precipitation during the cold months. The precipitation can be in the form of rain or snow. Recommendations: A 4 to 8 inch thick sub-base of washed and cleaned gravel should be used.

Hard Wet Freeze: those areas of the country where below freezing temperatures remain for long, continuous periods. The ground becomes fully saturated due to precipitation and melting of snow. Recommendations: Increase the sub-base of washed cleaned gravel to 8 to 24 inches, add air-entraining admixtures to the pervious concrete pavement mixture, and install a perforated PVC pipe in the thickened 8 to 24 inch gravel base to help capture and drain the water.

2.4.2 Abrasion

Surface abrasion is a potential problem. With the use of snow plows, shovels, and snow blowers in the winter time, and other hard contact applications like chains and tires during the other months, the ability of pervious concrete to resist abrasion is critical (Tennis et al 2004). Since the texture of pervious concrete differs from conventional concrete, the potential for raveling of aggregate particles and cracking is a serious issue. The ability of the pervious pavement system to resist these harsh treatments is critical to its long term durability.

The standard method of testing abrasion resistance is ASTM C944. A constant load of 98 N (22 lbs) is applied though a rotary cutting wheel (see Figure 2.10).

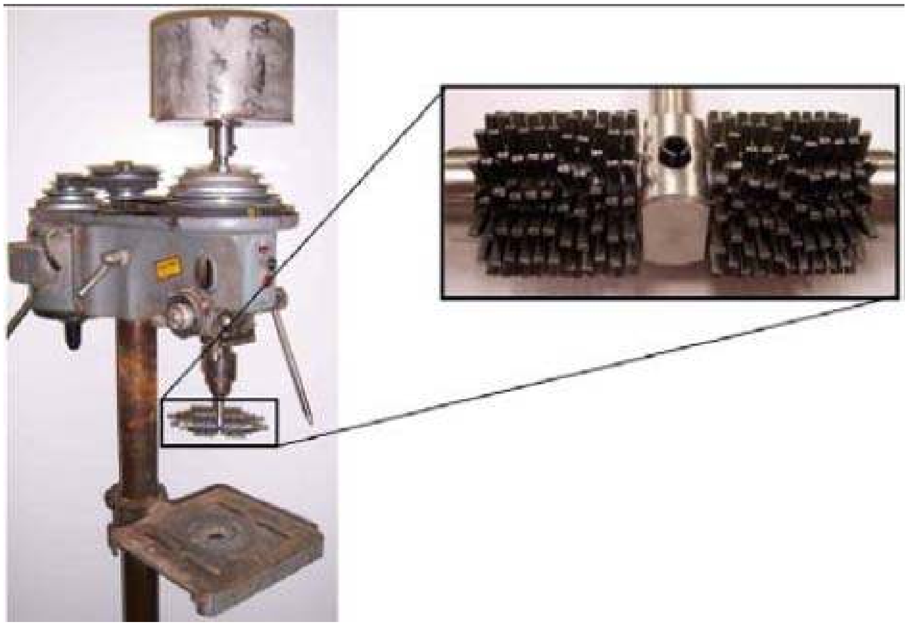


Figure 2.10: Surface Abrasion Testing Apparatus

The specimen is placed under a cutting wheel for a duration of 2 minutes. The loss of mass is then recorded. To improve the resistance to abrasion, a variety of surface applied applications as well as different curing methods were tested (Kevern et al 2009). Three curing compounds were tested and sprayed on pervious concrete samples. Of the three different types of curing compounds --standard white-pigment curing compound, a soybean oil emulsion curing compound, and a non-film-forming evaporation retardant -- the soybean oil had the biggest improvement in abrasive resistance (Kevern et al 2009).

Along with surface applied applications being tested for abrasion resistance, different methods of curing were also reviewed and tested. Proper curing of the concrete is important to allow the cement to hydrate and develop a strong concrete microstructure. While several approaches exist to help cure the concrete, some are not appropriate for pervious concrete. The bottom surface of the pervious concrete is exposed to air and moisture as well as the top surface. Covering the samples with a plastic sheet was thought to help several specimens enhance the abrasion resistance of pervious concrete. The samples were then cured in actual field conditions with a gravel sub-base and the results were compared to the standard air drying. It was found that curing with a plastic sheet placed over the sample showed a significant increase in abrasive resistance. For cases where surface applied curing compounds were used, the best performance for abrasive resistance was through the use of a plastic sheet (see Figure 2.11).

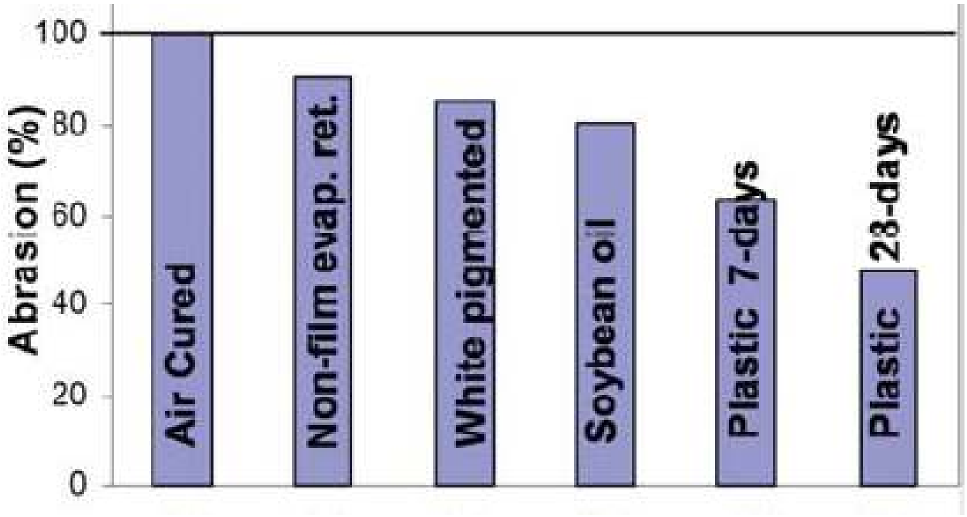


Figure 2.11: Results from Abrasion Resistance from Different Curing Compounds

2.4.3 Noise and Skid Resistance

To measure the skid resistance as it relates to the coefficient of friction, a Munro Stanley London British Pendulum Skid Resistance Tester was used on six different types of surfaces: dry, wet, snow, slush, compacted snow, and ice. Each surface was tested along with a standard dense asphalt mix.

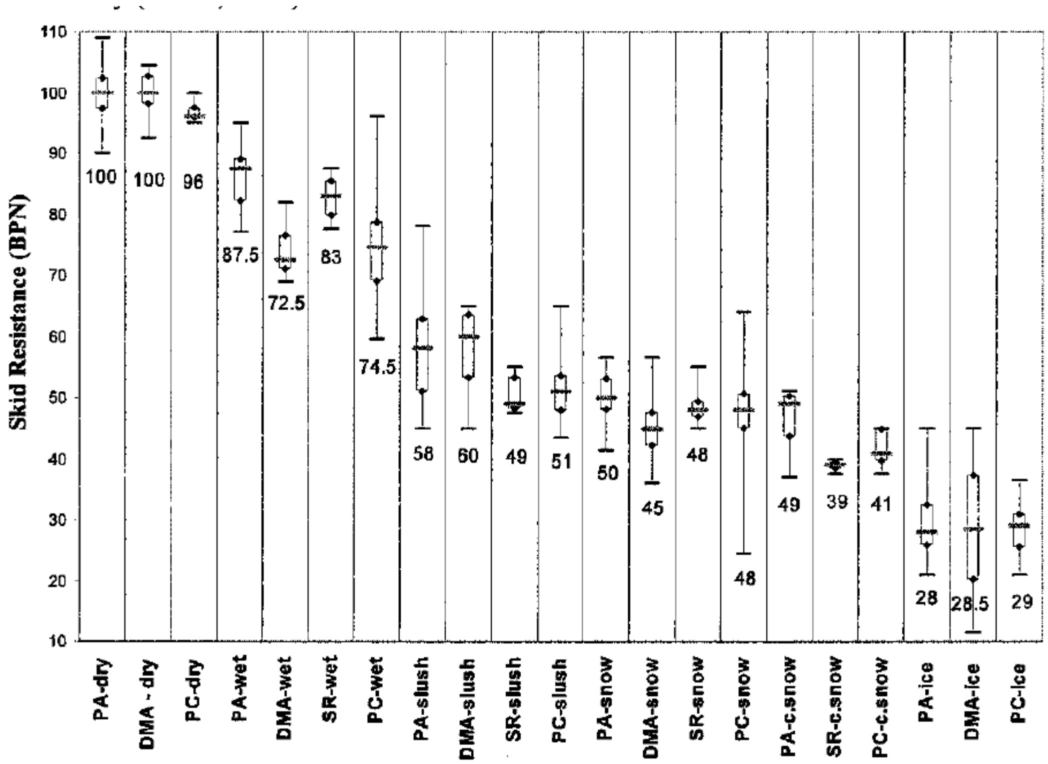


Figure 2.12: Results of Skid Resistance Test on Different Pavement Types; PA = Porous Asphalt; DMA = Dense-Mix Asphalt; PC = Pervious Concrete; SR = Standard Reference

For pervious concrete pavements, it was found that skid resistance was comparable to standard asphalt. The main difference was the amount of salt and sand needed for pervious concrete. Pervious concrete required 75% less sand and salt than standard asphalt.

Pervious concrete also has the ability to reduce the noise due to vehicles (ACI 522 Committee 2006). Through the open voids in the concrete, the amount of air pumping between the tire and road is minimized. By providing a reduction in traffic noise, this can potentially eliminate the need for costly noise barriers (Nelson et al 1994 and Descornet 2000).

Pervious concrete has a texture that is different from conventional concrete; it has an open voided surface that some have compared to "rice crispy treats". The open porous nature of pervious concrete has allowed sound to dissipate into the underlying sub-base.

2.5 Environmental Benefits

2.5.1 Filtration

Recent studies have shown that the sub-base is an effective means of capturing and eliminating harmful contaminants (Kwiatkowski et al 2007). Through proper design and maintenance, trace elements of copper and chloride can be absorbed within the infiltration sub-base and not impact the ground water.

Pervious concrete also has the ability to purify the stormwater as it percolates through to the sub-base (Park et al 2003). This so called "eco-concrete" has the ability to not only control and mitigate the amount of runoff from stormwater, but also reduce the environmental load on the surrounding ecosystem and purify the stormwater as it seeps through to the sub-base. By submerging the freshly cured pervious concrete in water to allow microorganisms to grow, nitrogen and phosphorous can be removed from the stormwater (Park et al 2003).

2.5.2 LEED Credit

Pervious concrete can be beneficial to building site designs by aiding in qualifying for LEED credits under the US Green Building Council (Ashley 2008). Under the LEED rating system, pervious concrete can contribute to the following credits:

Stormwater Design Credit: Using pervious concrete can contribute immensely to managing stormwater runoff as well as providing on-site infiltration and reducing contaminant loading before entering the groundwater.

Heat Island Effect – Non-roof credit: With lighter color than paved asphalt, pervious concrete has the ability to reflect solar radiation. The relatively open pore structure also stores less heat than paved asphalt.

Water Efficient Landscaping Credit: Trees and other landscaping have a hard time growing and thriving in covered areas due to the difficulty of getting water and air through the impervious pavements. Using pervious concrete reduces the need for potable water for irrigation.

Recycled Content Credit: As mentioned previously, the aggregate usage in the pervious concrete mix can contain a percentage of recycled aggregate and not compromise the integrity of the structural performance or durability of pervious concrete.

Regional Materials Credit: Similar to conventional concrete, pervious concrete can utilize much of the natural stone and other such aggregates that are local to the building site; thereby reducing the pollution needed to transport materials.

2.6 Construction and Maintenance

2.6.1 Sub-base Preparation

Creating a uniform sub-base is a critical component to an effective and efficient pervious pavement design (Tennis et al 2004). As stated previously, care must be used when compacting the sub-base soil. Over compaction will decrease the porosity of the soil and will not allow the pervious pavement to drain well. Under compaction could allow differential settlement in the pervious pavement which would result in cracking. Due to the minimal water in the pervious concrete mix, the sub-base must be moist prior to placement of the pervious concrete. If the sub-base is too dry, the soil will draw water from the pervious pavement and dry out the pavement prematurely (Tennis et al 2004).

2.6.2 Placement, Consolidation, and Joints

As with conventional concrete, there are a variety of ways to place pervious concrete. Due to the stiffness of pervious concrete, slump testing has been inadequate for quality acceptance. It has been suggested that unit weight tests provide the best measurement for quality control (Tennis et al 2004). Due to the low amount of water and high evaporation rates, placement should be continuous with rapid spreading and strike off (Tennis et al 2004). Vibrating and manual screeds should be used to help settle and level the pervious concrete (see Figure 2.13). Consolidation should then be accompanied with the use of a steel roller (see Figure 2.14) (ACI Committee 522 2006). It has been widely accepted that consolidation and compaction can play a very large role in compressive strength as well as permeability of concrete. It was reported that porosity varied linearly in concrete slabs 6 in. or greater (Haselbach et al 2006). This was due to the compaction methods using the steel roller.

Figure 2.13: Mechanical Vibrating Screed

Figure 2.14: Use of a Steel Roller

Figure 2.15: Use of a Rolling Joint Tool

Once the pervious concrete has been put in place, control joints should then be cut. Similar to conventional concrete, pervious concrete is subjected to random cracking due to hydration and shrinkage (Tennis et al 2004). It is recommended that joints should be spaced at a maximum of 45 feet with a depth of ¼ of the slab thickness (GCPA 1997 and Paine 1992). While saw cutting is possible although not preferred, the standard method of creating control joints has been with using a rolling joint tool (see Figure 2.15) (Tennis et al 2004). Since hydration and shrinkage are often imminent right after placement, joints should be placed soon after consolidation of the pervious pavement (Tennis et al 2004).

2.6.3 Maintenance

To help prolong the service life, an active maintenance program has shown to be beneficial in pervious concrete pavements. Over time, dirt and debris can get trapped and lodged within the voids of the pervious concrete pavement. With the dirt and debris creating an impervious layer within the pervious concrete pavement, water can then become trapped. Once this happens, freeze-thaw damage in the pervious pavement is possible.

Figure 2.16: Clogged Pervious Concrete Pavement

An active maintenance program starts with the initial planning of the site. The design and layout of the surrounding landscaping should eliminate the potential of flow of materials onto the pavement surface. Careful construction techniques should also be in place. Temporarily placing topsoil, mulch, etc. on the pavement should be avoided due to the potential of these materials seeping into the pervious concrete pavement.

Once the pervious pavement has been placed into service, an active regiment of vacuuming and power washing should be implemented. Several tests have shown that pressure washing of a clogged pervious pavement restored up to 80% of the permeability. Vacuuming is recommended to be done on an annual basis. This allows the easily removable debris to be swept before it has a chance to become trapped.

Figure 2.17: Vacuum for Sweeping Pervious Concrete Pavements

Vacuuming should be done prior to power washing. In a research report sponsored by RMC Research Foundation, testing was done to determine what proper active maintenance program was optimal to restore initial permeability. Core samples from various locations in Florida, Georgia, and South Carolina were taken and permeability was measured prior to remedial actions. Active maintenance in the form of pressure washing, vacuuming, and a combination of the two was then performed and found that in each case a 200% increase in permeability was achieved (Chopra et al 2007). It was noted that the pressure washing maintenance did allow potential pollutants that were trapped and lodged to freely flow to the sub-base.

Visual inspection should also be included as part of the active maintenance program. By actively evaluating and reviewing pervious pavements specifically after a heavy rain, problem areas can be easily identified. This can help with identifying clogged areas prior to a wintertime freeze.

Chapter Three

Experimental Methodology

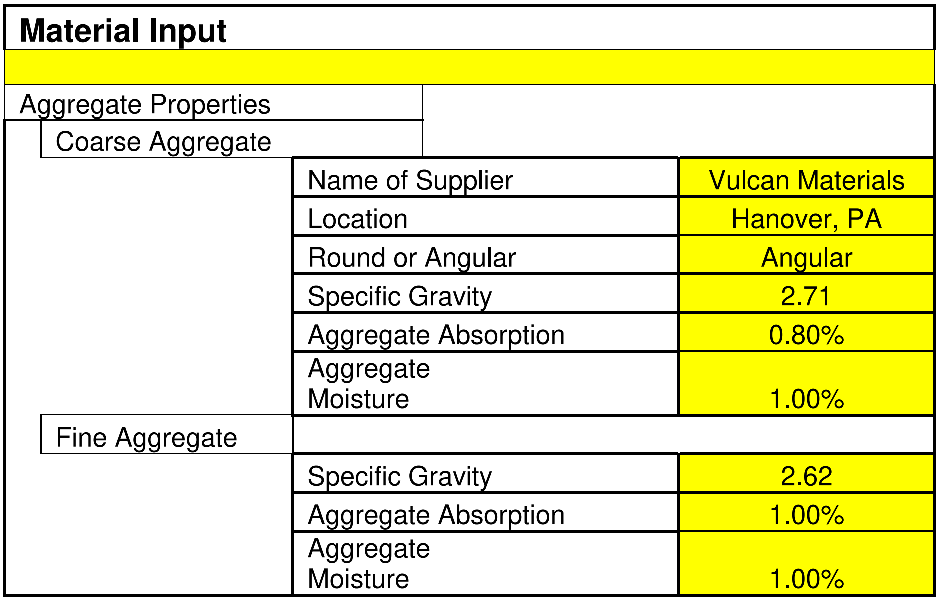
3.1 Overview

This chapter discusses the pervious concrete mix design, types of materials, and the procedures used for sample preparation. The research tested three different admixtures: viscosity modifier, delayed set modifier, and cellulose fiber.

3.2 Materials

To simulate mixtures for use in Maryland State Highway Administration (SHA) projects, materials often used for SHA projects were specified. Vulcan materials supplied the coarse and fine aggregates. The aggregates originated from their quarry in Hanover, PA and were distributed to the Annapolis Junction Yard in Maryland. Table 3.1 outlines the aggregate properties.

Table 3.1: Aggregate Properties



Material Input			
Aggregate Properties			
	Coarse Aggregate		
		Name of Supplier	Vulcan Materials
		Location	Hanover, PA
		Round or Angular	Angular
		Specific Gravity	2.71
		Aggregate Absorption	0.80%
		Aggregate Moisture	1.00%
	Fine Aggregate		
		Specific Gravity	2.62
		Aggregate Absorption	1.00%
		Aggregate Moisture	1.00%

A maximum of 1/2 in. diameter aggregate was used in each mix design. Fine aggregates were used to help achieve higher design strengths. Portland Type I cement was used in each mix. One control mix and three mix designs with the following admixture were batched: viscosity modifier, delayed set modifier, and cellulose fibers. The following matrices shown in Figures 3.1-3.6 were developed for the different batches and different tests to be performed:

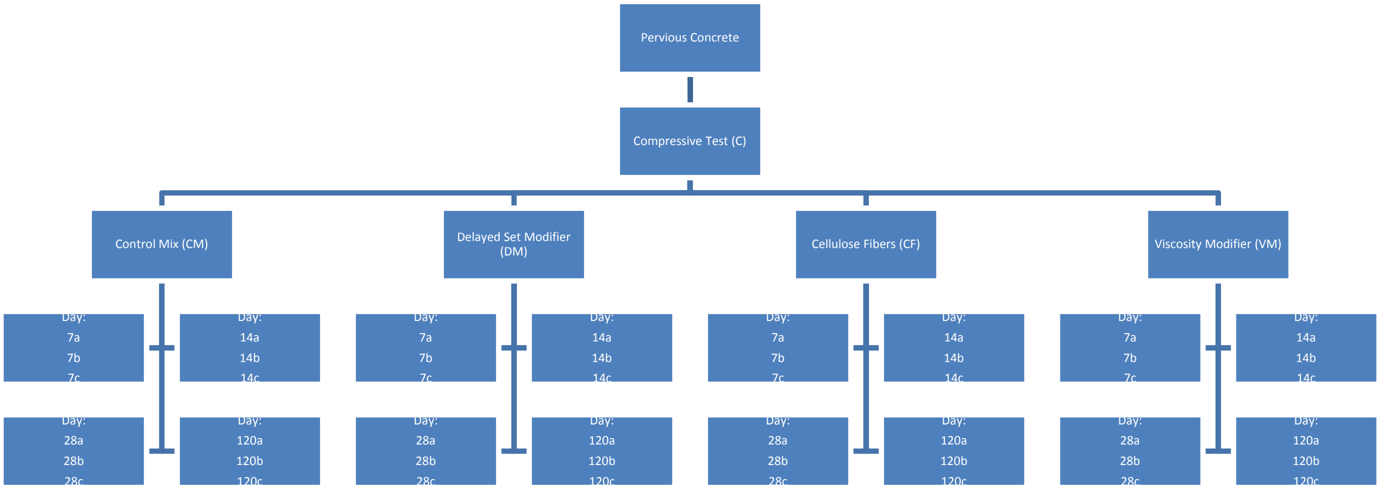


Figure 3.1: Compressive Strength Test Matrix

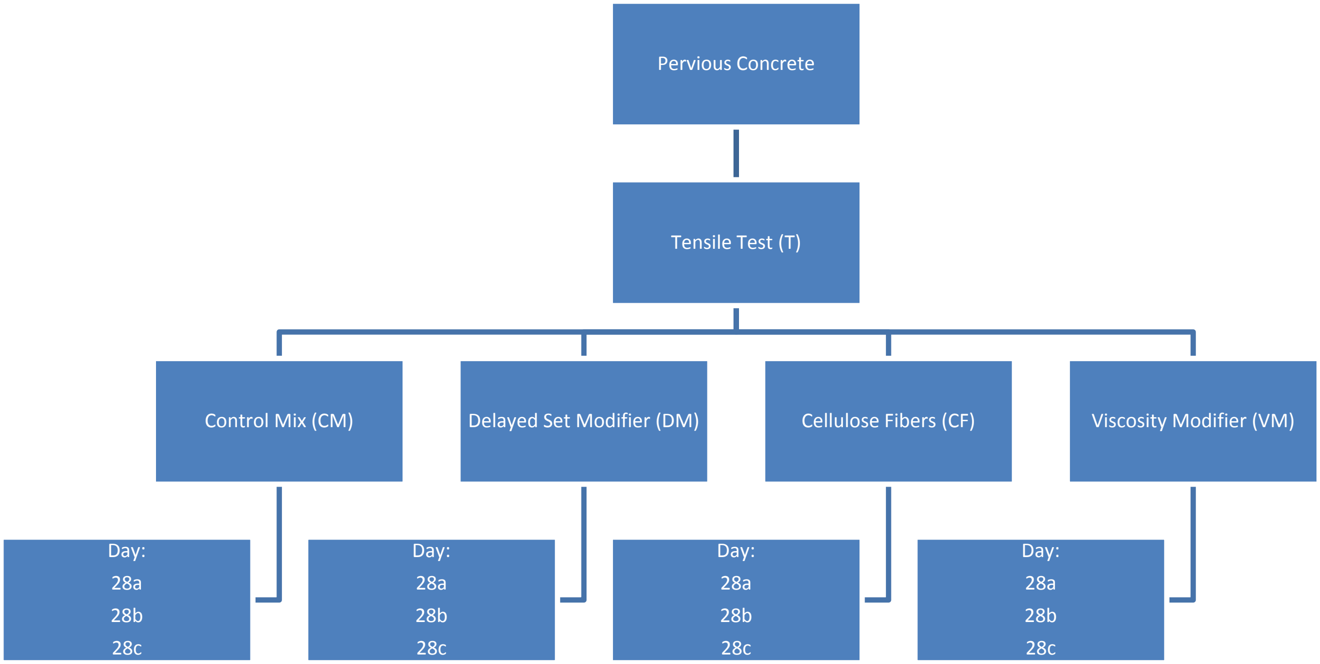


Figure 3.2: Tensile Strength Test Matrix

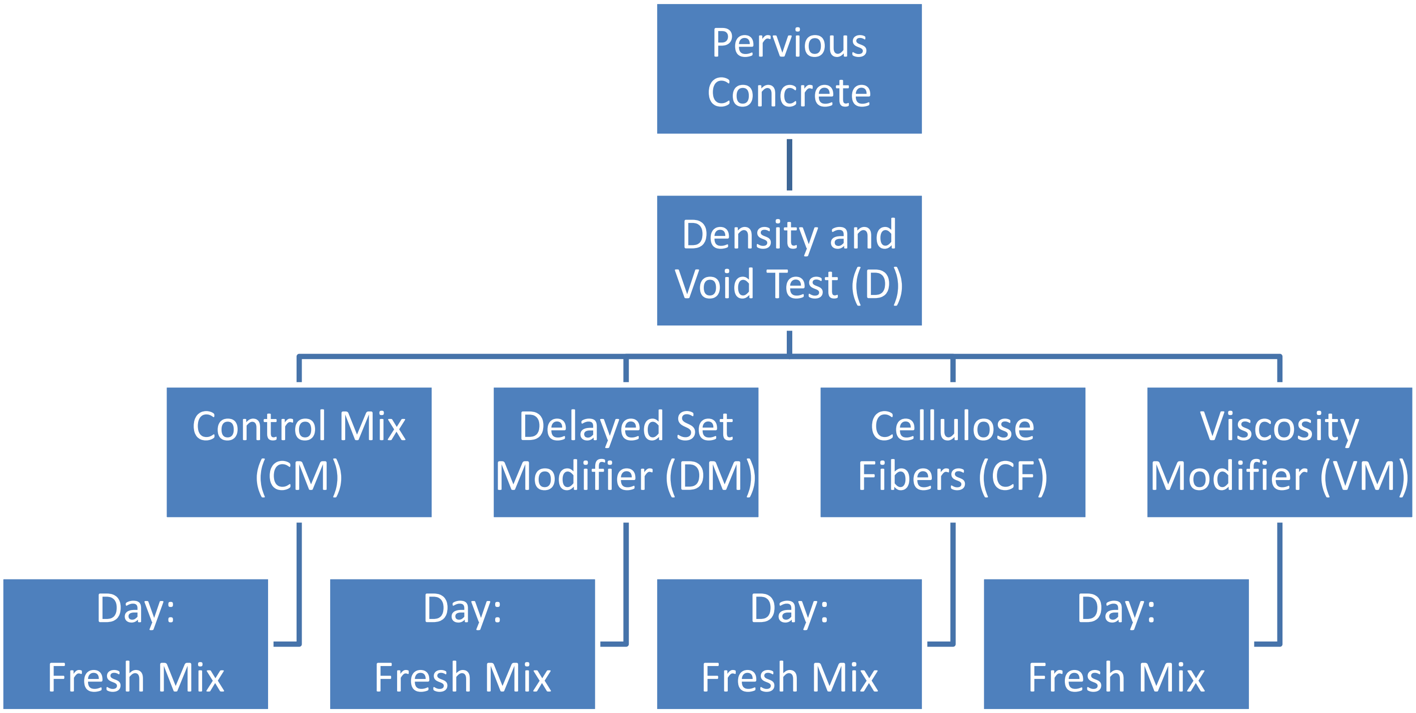


Figure 3.3: Density and Void Test Matrix

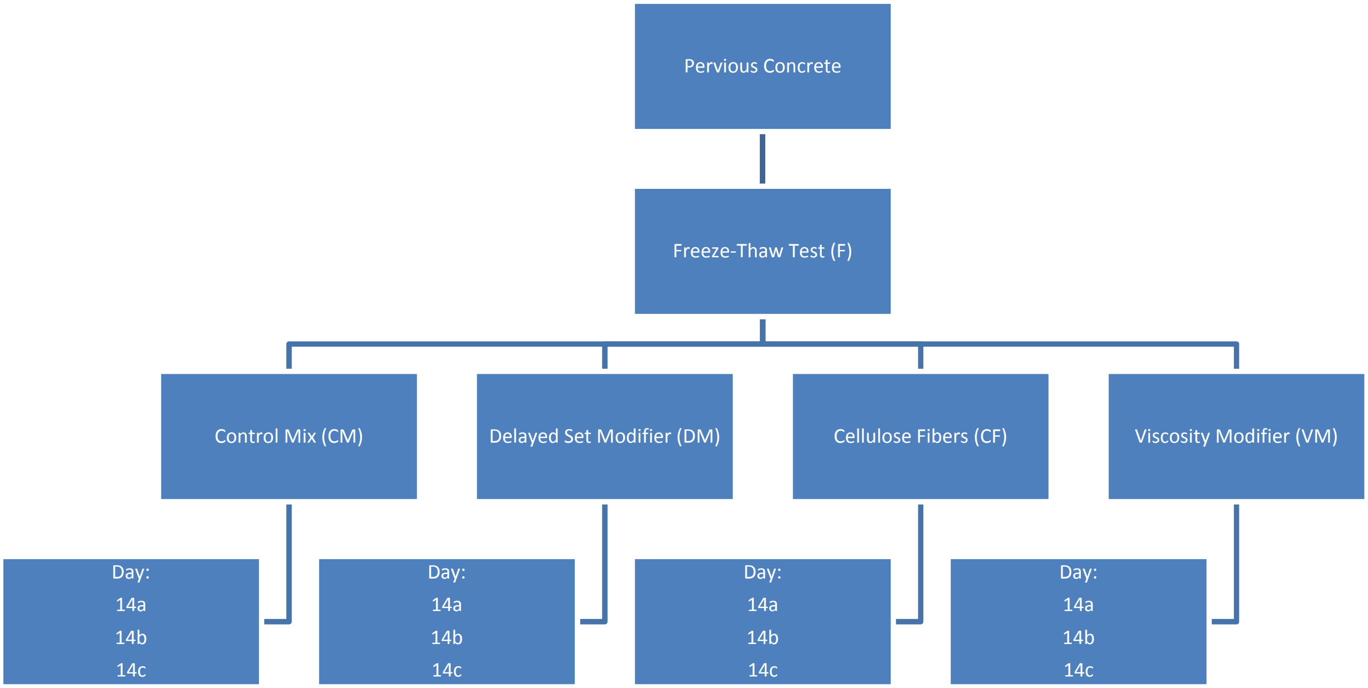


Figure 3.4: Freeze-Thaw Test Matrix

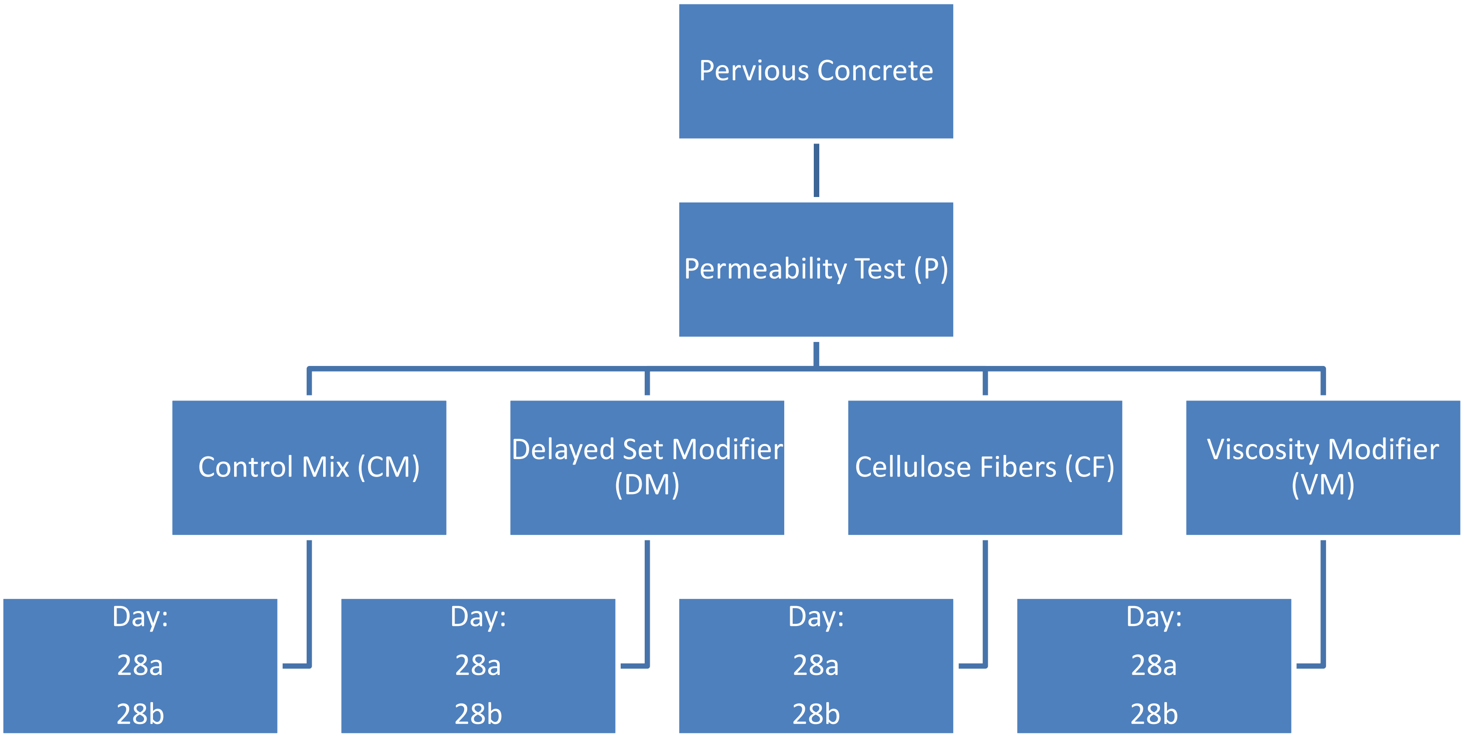


Figure 3.5: Permeability Test Matrix

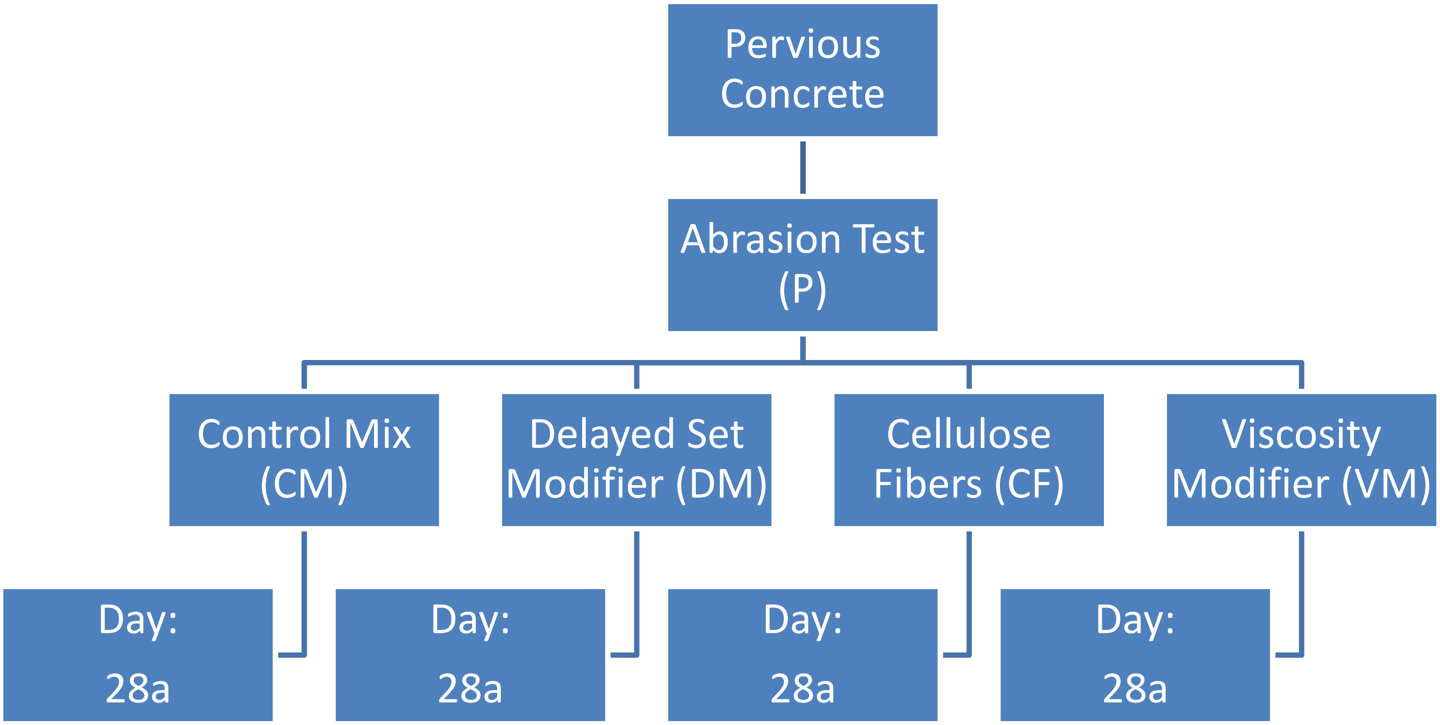


Figure 3.6: Abrasion Test Matrix

The following notations were used to identify the mix designs:

Control mix: CM
Delayed Set Modifier mix: DM
Cellulose Fiber mix: CF
Viscosity Modifier mix: VM

In addition, the following notations were used to identify each test:

Compression Test: C
Tension Test, Split Cylinder: T
Density and Void Test: D
Freeze/Thaw Test: F
Permeability Test: P
Abrasion Test: A

Viscosity Modifier Admixture (VMA): Compared to conventional concrete, pervious concrete is a harsh mix because it contains little or no fine aggregate. Commercially available VMA has been developed to add body and help lubricate pervious concrete mixes. The anticipated results are better flow, faster discharge time from a truck, and easier placement and compaction of an otherwise dry, harsh mix. In addition, the use of a VMA provides insurance against paste drain down. Paste drain down is a condition in which too fluid a cement paste in pervious concrete migrates to the bottom of the slab, due to gravity, and seals it. This sealing of the bottom surface makes the pervious concrete functionally useless and can be avoided through use of a VMA. Experimental tests were conducted to determine if the VMA also increases compressive and flexural strength in low compaction pervious concrete mixes by enhancing the paste to aggregate bond. It should be noted that while all VMAs alter the rheology, or flow behavior of a concrete mix, each VMA can have different effects on the mix based on its specific chemistry. Some VMAs have been used in pervious concrete with less than desirable results. Some VMAs work by binding water in a concrete mix, thereby changing its viscosity. With pervious concrete, this mechanism works against the system by making the concrete even more difficult to place because of increased stiffness. The interest here is to determine if this potential admixture can be used to increase structural and durability effects.

Delayed Set Modifier Admixture: A major concern with concrete producers is the difficulty in discharging and placing/finishing pervious concrete within a relatively short time span. With low water-to-cement ratio and lack of fine aggregates, discharging and finishing pervious concrete is often a difficult and aggravating task. The relatively short working time window with pervious concrete often leads to a very fast paced, labor intensive effort. Incorporating a delayed set modifier admixture into the pervious concrete mix design will inevitably allow a longer working window for placement. While this is obviously beneficial for construction practices, the mechanical properties of pervious concrete would need to be evaluated to determine what effect this has on allowing pervious concrete to remain plastic longer.

Cellulose Fibers: Cellulose fibers have been gaining popularity as an alternative for polypropylene fibers. While polypropylene fibers have been used in some Maryland pavement designs, the process for producing these fibers is considered environmentally harmful. Instead, a renewable source of fibers was considered. Recently, cellulose fibers have been adopted by many building codes, including IBC. These fibers are derived and manufactured from natural products and can enhance the mechanical properties (tensile and flexural strength) in concrete. It is a green product and has been gaining a lot of attention. Modern cellulose fibers for use in reinforcing concrete are based on a virgin, purified form of the cellulose fiber. The natural polymer that cellulose is derived from is a cost effective renewable source. Research by Brown and Morton (2010) for ready-mix concrete showed improved durability for concrete exposed to temperature variations.

One major project in which cellulose fibers were used with pervious concrete was the Bus Transit Station in Middle Tennessee State University (MTSU). Cellulose fibers were introduced into the mix to help reduce micro-cracking. While the study is still ongoing, the reported outcome is very promising for applications in weather exposed areas. A recent paper “Study of Pervious Concrete for Use in Pavements” by Fortes, Merighi, and Bandeira (2006) compared the use of cellulose fibers to polypropylene fibers in concrete and found some differences between the two fibers – cellulose fibers were found to be more advantageous.

Cellulose fibers have some significant advantages including a renewable source of material, reduction in shrinkage and temperature cracking, and fiber balling. These fibers have a few drawbacks. One of the major drawbacks is that the fibrous pulps are not resistant to alkaline or other fungi and algae attacks. To help prevent this and strengthen the cellulose fibers, the outer surfaces of each fiber are coated and treated with a biocide material. This biocide material is an alkaline resistant coating that does not impede the bonding of the cement paste to the fiber.

3.3 Mix Design

While pervious concrete contains the same basic ingredients as the more common conventional concrete (ie. aggregate, Portland cement, water, and a variety of admixtures), the proportioning of ingredients is quite different. One major difference is the requirement of increased void space within the pervious concrete. The amount of void space is directly correlated to the permeability of the pavement. With low water to cement ratio, the need for void space within the mix design, and little to no fine aggregates, the conventional design of concrete needs to be adjusted accordingly. Ranges of materials commonly associated with pervious concrete are listed below. These ranges are based on previous research.

Design Void Content: 15% to 25%
Water to Cement Ratio: 0.27 to 0.33
Binder to Aggregate Ratio: below 0.25

The goal for the final mix design was to provide a strong, durable pervious concrete design which allowed for adequate drainage of rainwater. Reviewing the literature and past research, a 15% design void content would have allowed for higher strength and durability in the pervious concrete samples but not allowed adequate drainage based on Maryland peak storm events. A 25% void content would have allowed more than enough void space in the samples to accommodate a peak storm even in Maryland but may not have provided the strength and durability that was required for the research project. Taking into account the goals of the project and the literature review, a target void content of 20% was desired with a water-to-cement ration of 0.3. Prior to the application of the admixtures, several test mixes were performed to determine an appropriate mix design for the project. While trying to increase strength and maintaining permeability, different values of water to cement ratio were tested. Three different water-to-cement ratios were tested: 0.27, 0.30, and 0.33. Three cylinders, 4 inch diameter by 8 inch tall were cast for each ratio. During mixing, it was noted that the lowest water-to-cement ration of 0.27 was very dry. The cylinders were demolded after 24 hours and allowed to cure in a water tank. After three days, it was visually observed that the lowest water-to-cement ratio had several loose aggregates not bonded together. Comparing to the literature review, past research, and the sample mix designs performed, the mix design noted in Table 3.2 was selected.

Table 3.2: Concrete Mixture Properties

Required Pervious Concrete Mixture Properties				
	Design Void Content	20.00%		
	Water to Cement Ratio	0.3		
	Supplemental Cementitious Material		0	
Required Materials	Design for 1 cy of concrete			
		Weight (lbs)	Volume	
	Coarse Aggregate	2426	53.10%	
	Fine Aggregate	183	4.10%	
	Cementitious Material	620	11.70%	
	Water	181	11.00%	
	Water Gallons	21.7		
	Volumetric Void Content	20.00%		
	Design Unit Weight	126.4		pcf

The standard mix proportions for the mix were as follows:

Cement: Coarse Aggregate: Fine Aggregate: Water which will be equivalent to 1:4.1:0.30:0.30 by weight. The pervious concrete mix design that was used for this research project was determined from a thorough literature review of past research.

The total amount of concrete to conduct the six tests (Compression Test, Tensile Test, Permeability Test, Density and Void Test, Freeze-Thaw test, and Abrasion Test) required is 0.28 cubic yard. Table 3.3 is a breakdown of materials needed per test:

Table 3.3: Material Quantities

	Test			
	CM	DM	CF	VM
Portland Cement (lbs)	43.4	43.4	43.4	43.4
Coarse Aggregate (lbs)	170	170	170	170
Fine Aggregate (lbs.)	12.81	12.81	12.81	12.81
Water (lbs)	12.67	12.67	12.67	12.67
Delayed Set Modifier (fl oz)	X	.56	X	X
Cellulose Fibers (lbs.)	X	X	.5	X
Viscosity Modifier (fl oz)	X	X	X	.56

3.4 Mix Procedure

The pervious concrete for the four mixes were prepared in four separate batches using a rotating drum concrete mixer.

Figure 3.7: Mixing Drum Used

The coarse aggregate was sieved and all larger aggregates were removed. The aggregates were then weighed and separated into four different batches. The fine aggregates were allowed to air dry overnight to remove moisture. They were then weighed and separated. The rotating drum mixer was cleaned and dried. Water and admixtures were weighed and placed next to their respective batches. The drum mixer was started and about 5-10% of the Portland Type I cement and water was added to the coarse aggregate. The rotating drum was turned on and the materials were mixed for one minute. The remaining cement, fine particles, water, and aggregate were added to the rotating drum and mixed. The entire mixture was mixed for three minutes. The mixture was then allowed to rest for three minutes and then was mixed again for another two minutes.

The mixture was then reviewed for consistency by taking a handful of pervious concrete mix and creating a ball. If the aggregate separated and did not maintain the ball shape, the mixture was considered too dry. If the ball had a lot of paste running off the aggregate and sticking to the glove, then the mixture was considered too wet. Although this is subjective, this has been considered a common practice in the industry.

Once the observations were noted, the density and void ratio test was conducted. The discussion of this test can be found in Chapter 4. The mixtures were then placed in cylinders or prisms. With the exception of the 6 in. diameter x 12 in. long cylinders, each cylinder or prism was filled halfway to the top. Each specimen was then rodded 25 times equally around the sample. The specimens were then filled 1/2 in. above the top and rodded again 25 times evenly around. With the 6 in. diameter x 12 in. long specimens, each sample was filled 1/3 to the top and then rodded. The specimens were then struck-off at the top and covered. After 24 hours, the cylinders or prisms were removed from their molds and placed in a curing box. The curing box was a wet tank kept at room temperature. Three technicians were used to help mix and mold all of the specimens.

Chapter Four

Experimental Tests and Results

4.1 Density and Void Ratio

ASTM C1688 has become one of the few accepted tests that can adequately determine effective pervious concrete mix properties such as density and void content. This test helps to determine if the freshly mixed concrete will achieve the targeted void content as specified in the mix design. The test was conducted at the University of Maryland and was done by first obtaining a cylindrical steel container with a minimum capacity of .25 cubic feet. The inside was moistened with a damp towel and excess water was removed from the bottom. The container was then weighed and the weight recorded to the nearest gram. The freshly mixed pervious concrete was scooped into the container and once it was approximately half full, a standard proctor hammer was used to compact the specimen. The hammer was dropped 20 times evenly around the cylindrical area. The container was then filled ¼ of an inch above the top lip. The proctor hammer was used again to compact the specimen using 20 evenly distributed blows. A hand trowel was used to strike off the top surface of the container and a clean towel was used to wipe down the sides. The cylinder was then weighed and the weight recorded to the nearest gram. The weight of the pervious concrete sample was found by subtracting the total weight of the cylinder and sample from the measured weight of the container.

Figure 4.1: Apparatus Used for Density and Void Content

The density and void content was found by first determining the theoretical density of the concrete computed on an air-free basis. This is computed by dividing the total mass of all materials batched by the sum of the absolute volumes of the component ingredients in the concrete mix. Densities of the different mix designs of pervious concrete are noted in Table 4.1.

Table 4.1: Density and Theoretical Density of the Pervious Concrete

Density of the Mix			
	Control Mix	128.98	pcf
	Delayed Set Modifier	127.23	pcf
	Viscosity Modifier	128.39	pcf
	Cellulose Fiber	130.53	pcf
Theoretical Density of the Concrete:			
	S.G. Coarse Aggregate	2.71	
	S.G. Fine Aggregate	2.62	
	S.G. Portland Cement	3.15	
	S.G. Fibers	1.1	
	Coarse Aggregate Mass	2426	lbs
	Fine Aggregate Mass	183	lbs
	Portland Cement Mass	620	lbs
	Water Mass	181	lbs
	Fiber Mass	2	lbs

The absolute volumes were determined by taking the quotient of the mass of the ingredient divided by the product of its relative density times the density of water. The specific gravities for the coarse and fine aggregates were given by the aggregate supplier. The Portland cement was assumed to have specific gravity of 3.15 as stated in ASTM C 1688. Equation 1 denotes the theoretical density of the concrete computed on an air-free basis:

$$T = M_s/V_s \quad \text{……………………………………………………………………….Eq.1}$$

To calculate the actual mix density, the mass of the concrete filled container must be subtracted from the mass of the container and then divided by the volume of the container. Equation 2 denotes the density of the pervious concrete mix:

$D = (M_c - M_m)/V_m$………………………………………….……………………...Eq.2

The void content of the sample was found by the following equation:

$U = (T-D)/T \times 100\ \%$……………………………………...…………………Eq.3

The target void content of the mix design was 20%. As shown in Table 4.2, all four mix designs are within an acceptable range. The cellulose fiber mix had the lowest void content. This was primarily due to the fibers taking up a small portion of the void content.

Table 4.2: Calculated Void Content

Void Content:			
	Control Mix	19	%
	Delayed Set Modifier	20	%
	Viscosity Modifier	19	%
	Cellulose Fiber	18	%

4.2 Compressive Strength Test

The compressive strength test was performed on all four mix designs. Three cylinders were cast from each mix design and the average of the compressive strength was used as the final number. Four different periods were used to determine the rate at which the cylinders gained strength – Day 7, Day 14, Day 28, and Day 120. The test was performed at a University of Maryland Laboratory. The specimens were removed from the curing box at the day of testing and wiped clean. The diameter of each specimen was measured at the top, middle, and bottom. The average of the three diameters was used to calculate the cross-sectional area. Any specimen having a diameter varying more than 2% of any other measured diameter was not used in the compression test. All the pervious concrete samples met this requirement. The specimens were then placed under the center ring of the compression machine. The test machine used was hydraulically powered. The upper bearing block was stationary, while the lower bearing block moved up to compress the specimen. The upper bearing block was capable of tilting if the top of the specimen was not completely horizontal. Prior to testing, the surfaces of the testing machine were wiped clean. The test cylinder was then placed on the lower bearing block and centered. The load was applied at a rate corresponding to a stress increase between 28 psi/sec and 42 psi/sec. Each specimen was loaded until the load began to decrease rapidly, and a fracture was clearly evident. The maximum load applied was then recorded. The procedure was repeated at the interval of days noted earlier.

Figure 4.2: Pervious Concrete Specimen in Compression Testing Machine

Table 4.3: 7 Day Compressive Strength Results

Day 7 Test	3-Oct-10						
	Control Mix 1	25640	lbs		2041.401	psi	
	Control Mix 2	24020	lbs		1912.42	psi	
	Control Mix 3	20200	lbs		1608.28	psi	
						1854.034	psi
	Delayed Set Modifier 1	32900	lbs		2619.427	psi	
	Delayed Set Modifier 2	29500	lbs		2348.726	psi	
	Delayed Set Modifier 3	25040	lbs		1993.631	psi	
						2320.594	psi
	Viscosity Modifier 1	11520	lbs		917.1975	psi	
	Viscosity Modifier 2	18500	lbs		1472.93	psi	
	Viscosity Modifier 3	10900	lbs		867.8344	psi	
						1085.987	psi
	Cellulose Fiber 1	26260	lbs		2090.764	psi	
	Cellulose Fiber 2	16000	lbs		1273.885	psi	
	Cellulose Fiber 3	22540	lbs		1794.586	psi	
						1719.745	psi

Table 4.4: 14 Day Compressive Strength Results

Control Mix 1	42020	lbs		3345.541	psi	
Control Mix 2	38880	lbs		3095.541	psi	
Control Mix 3	28570	lbs		2274.682	psi	
					2905.255	psi
Delayed Set Modifier 1	49710	lbs		3957.803	psi	
Delayed Set Modifier 2	35360	lbs		2815.287	psi	
Delayed Set Modifier 3	44000	lbs		3503.185	psi	
					3425.425	psi
Viscosity Modifier 1	13890	lbs		1105.892	psi	
Viscosity Modifier 2	23120	lbs		1840.764	psi	
Viscosity Modifier 3	17470	lbs		1390.924	psi	
					1445.86	psi
Cellulose Fiber 1	42550	lbs		3387.739	psi	
Cellulose Fiber 2	35650	lbs		2838.376	psi	
Cellulose Fiber 3	32910	lbs		2620.223	psi	
					2948.779	psi

Table 4.5: 28 Day Compressive Strength Results

Control Mix 1	26240	lbs		2089.172	psi	
Control Mix 2	28050	lbs		2233.28	psi	
Control Mix 3	39020	lbs		3106.688	psi	
					2476.38	psi
Delayed Set Modifier 1	24100	lbs		1918.79	psi	
Delayed Set Modifier 2	23540	lbs		1874.204	psi	
Delayed Set Modifier 3	29550	lbs		2352.707	psi	
					2048.567	psi
Viscosity Modifier 1	43010	lbs		3424.363	psi	
Viscosity Modifier 2	27170	lbs		2163.217	psi	
Viscosity Modifier 3	17750	lbs		1413.217	psi	
					2333.599	psi
Cellulose Fiber 1	45250	lbs		3602.707	psi	
Cellulose Fiber 2	38050	lbs		3029.459	psi	
Cellulose Fiber 3	38330	lbs		3051.752	psi	
					3227.972	psi

Table 4.6: 120 Day Compressive Strength Results

Control Mix 1		29520	lbs		2350.318	psi	
Control Mix 2		37840	lbs		3012.739	psi	
Control Mix 3		31150	lbs		2480.096	psi	
						2614.384	psi
Delayed Set Modifier 1		22680	lbs		1805.732	psi	
Delayed Set Modifier 2		32450	lbs		2583.599	psi	
Delayed Set Modifier 3		36280	lbs		2888.535	psi	
						2425.955	psi
Viscosity Modifier 1		40250	lbs		3204.618	psi	
Viscosity Modifier 2		29660	lbs		2361.465	psi	
Viscosity Modifier 3		29990	lbs		2387.739	psi	
						2651.274	psi
Cellulose Fiber 1		31610	lbs		2516.72	psi	
Cellulose Fiber 2		46480	lbs		3700.637	psi	
Cellulose Fiber 3		42180	lbs		3358.28	psi	
						3191.879	psi

Tables 4.3-4.6 contain the results of the 7, 14, 28, and 120 day compressive strength results respectively. Each specimen was loaded until the load began to decrease rapidly and a well-defined fracture appeared.

The compressive strength was calculated by dividing the final maximum load recorded by the cross-sectional area of the cylindrical specimen. If the specimens had a Length-to-Diameter ratio less than 1.75, the compressive strength calculated must be modified with a correction factor. If the Length-to-Diameter ratio is greater than 1.75, no correction factor is needed. Since the ratio for all specimens exceeded 1.75, no correction factor was used.

The average 28 day compressive strength varied from 2048 psi to 3227 psi. The low variation in the compressive strength can be attributed to the same method of compaction of the specimens. Each specimen was compacted at two lifts – one at the mid height and the other at the top. It has been discussed that for pervious concrete samples there is a high degree of correlation between compressive strength and the method of compaction. Due to the open voided structure of the pervious concrete, the more compaction each sample receives, the more these voids tend to close. The relationship between compressive strength and void ratio can be seen in Figure 4.3.

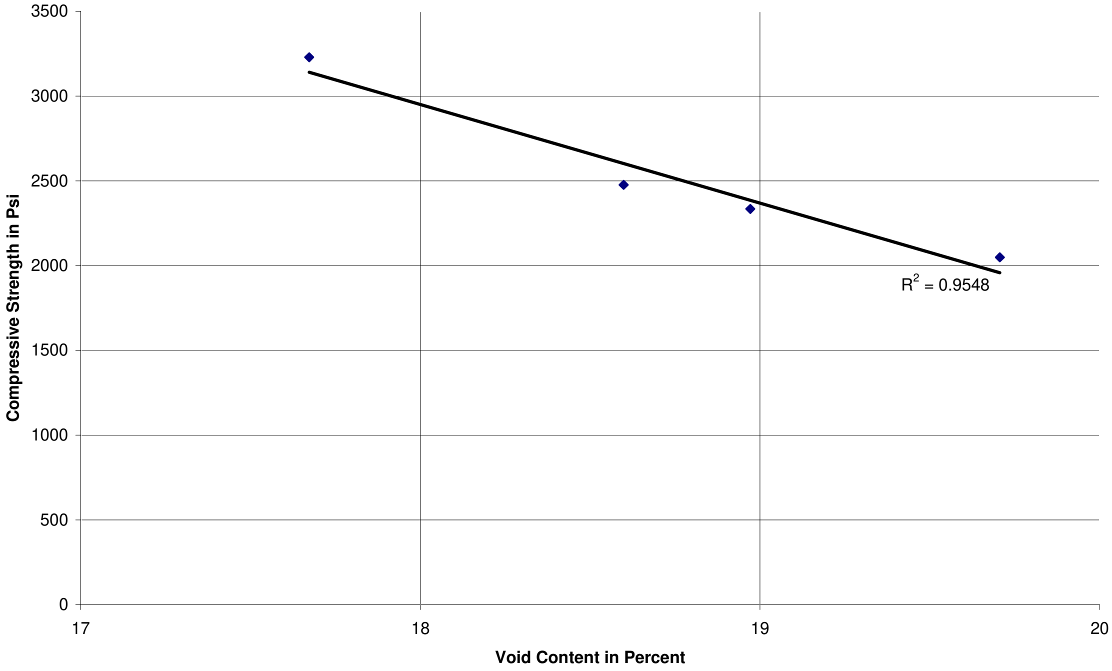


Figure 4.3: Correlation between Void Content and Compressive Strength

4.3 Split Cylinder Test

A split tensile strength test was performed for all samples cured at 28 days as specified in ASTM C496. While there have not been any standard tests adopted by

ASTM to provide a direct measurement of the tensile strength of pervious concrete, ASTM C 496 has been used in a wide variety of other research.

This test measures the tensile strength of a concrete sample by compressing a cylinder through a line load applied along its length. This test can be completed in a standard compression testing machine. The test was conducted on the same machine as the compressive test at the University of Maryland.

A uniform tensile stress is created over the cylinder's diameter along the plane of loading. The maximum tensile stress occurs at the center of the cylinder. ASTM C496 indicates that the maximum tensile stress can be calculated based on Equation 4. In this equation, P is the load applied to the cylinder, l and d are the length and diameter, and T is the tensile stress.

$$T=2P/\pi ld \quad \text{Eq.4.}$$

For the pervious concrete specimens, each sample was removed on day 28 of curing from the curing box and wiped clean. Two diagonal lines were then drawn at the center of each specimen with a permanent marker. The diameter of the specimen was measured at three locations, top, middle, and bottom and the results were averaged. A wooden bearing strip 1/8 in. thick was placed on the bottom bearing block. The pervious concrete specimen was then placed on the bearing strip, aligned with the center. The top bearing strip was aligned with the pervious concrete sample. The bottom bearing block was then hydraulically elevated. The machine was started at the loading rate of 150 psi/min. When the specimen broke, the load was recorded.

Figure 4.4: Split Tensile Strength Test with Bearing Strips Prior to Loading

Table 4.7: Tensile Strength Results

Control Mix 1	4200	lbs		334.3949	psi	
Control Mix 2	3300	lbs		262.7389	psi	
Control Mix 3	3600	lbs		286.6242	psi	
					294.586	psi
Delayed Set Modifier 1	4500	lbs		358.2803	psi	
Delayed Set Modifier 2	4100	lbs		326.4331	psi	
Delayed Set Modifier 3	5400	lbs		429.9363	psi	
					371.5499	psi
Viscosity Modifier 1	2200	lbs		175.1592	psi	
Viscosity Modifier 2	3100	lbs		246.8153	psi	
Viscosity Modifier 3	2800	lbs		222.9299	psi	
					214.9682	psi
Cellulose Fiber 1	4500	lbs		358.2803	psi	
Cellulose Fiber 2	6500	lbs		517.5159	psi	
Cellulose Fiber 3	5000	lbs		398.0892	psi	
					424.6285	psi

Not surprisingly, the split tensile strength was considerably low with cellulose fibers exhibiting the highest amount of tensile stress. Figure 4.5 shows the relationship between compressive strength and tensile strength. Clearly, there is no real correlation between compressive strength and tensile strength of the pervious concrete samples.

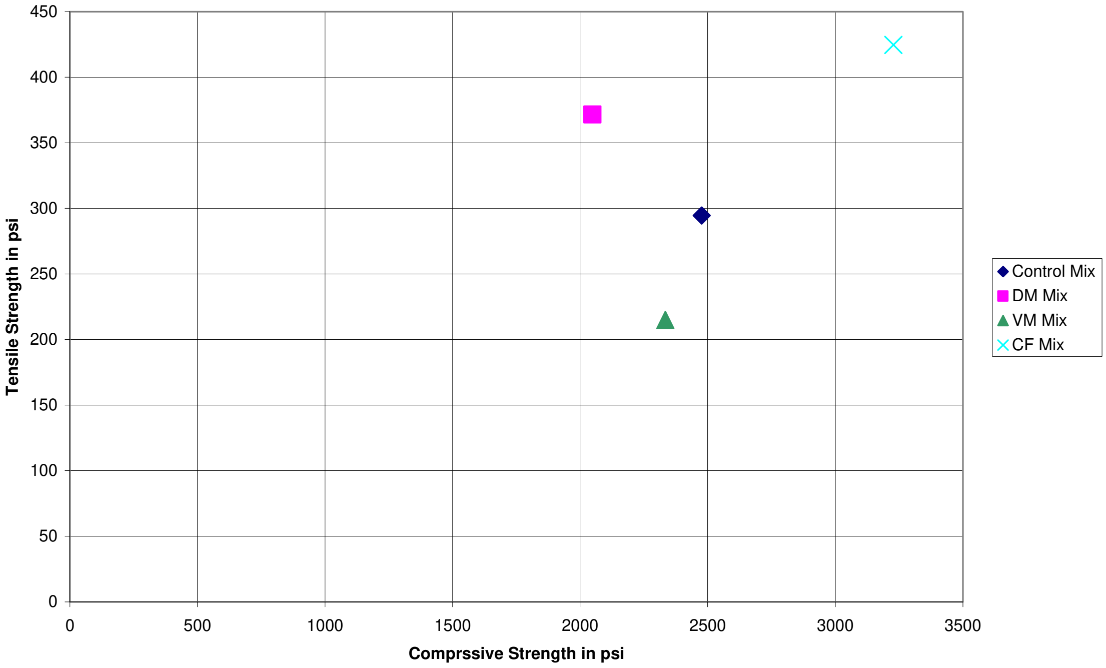


Figure 4.5: Comparison between Compressive Strength and Tensile Strength

4.4 Permeability Test

Permeability was determined using the falling head method through a permeameter. At the time of testing, there were no approved standards for measuring permeability in pervious concrete samples. The falling head apparatus has been used successfully at the National Ready Mix Concrete Association (NRMCA) with past pervious concrete samples. NRMCA engineers were consulted and several demonstrations were performed.The test originated from ASTM 522 as an acceptable means of measuring permeability in pervious concrete. The falling head method has been used successfully in past research. The test was conducted at Eastern Testing and Inspection Laboratory in Frederick, Maryland. Samples used in the permeability test were four inches in diameter and eight inches in length. Each sample was removed from the curing box after 28 days of curing and wiped clean. The sample was then wrapped from top to bottom in a flexible sealing gum to prevent water leakage along the sides of the sample. A clear PVC tube was connected to the top of the sample by an oversized rubber hose clamp. The clamps were screwed tight and checked for leakage. A clear

PVC pipe was used to allow the water height to be read as it dropped down the sample. Standard PVC pipes were used for the remainder of the apparatus. A separate oversized rubber hose clamp was used to connect the bottom of the specimen to the standard PVC pipe. A rubber stopper was used at the end of the standard PVC pipe. Once all the pieces were setup, the stopper was put in and the apparatus was filled with water. No leakage was apparent. The rubber stopper was removed and the specimen was allowed to drain. This allowed the pervious concrete specimen to become fully saturated prior to testing. Once the water height reached equilibrium, the rubber stopper was applied and water was added to the clear PVC pipe. Markings for the water height were noted on the clear PVC pipe.

Figure 4.6: Materials Used for Falling Head Permeability

Figure 4.7: Assembled Falling Head Permeability Test

The rubber stopper was released and the time was recorded. The coefficient of permeability (k) was determined by Equation 5:

$$k = (aL/At)LN(h1/h2) \quad \text{Eq.5}$$

Where k = coefficient of permeability (in/hr), a = cross sectional area of the standpipe (in^2), L = length of the specimen (in), A = cross sectional area of the specimen (in^2), t = time for water level to reach from h1 to h2 (sec.), h1 = initial water level (in), and h2 = final water level (in). Table 4.8 contains the results of the permeability tests.

Table 4.8: Permeability Results

Date of Test	10/24/2010	Permeability in/hr.		
	Control Mix 1	417		
	Control Mix 1b	400		
	Control Mix 1c	412		
	Delayed Set Modifier 1a	420		
	Delayed Set Modifier 1b	410		
	Delayed Set Modifier 1c	417		
	Viscosity Modifier 1a	405		
	Viscosity Modifier 1b	420		
	Viscosity Modifier 1c	417		
	Cellulose Fiber 1a	417		
	Cellulose Fiber 1b	405		
	Cellulose Fiber 1c	410		

All of the specimens that were tested had very similar permeability results. Permeability is highly correlated to void ratio; and since the void ratios varied from 18%-20%, the permeability results were also fairly similar as expected. Permeability coefficients for actual field conditions would be different from the laboratory results due in part to potential clogging of the pervious pavement, underlying soil conditions, and compaction methods which are all factors that would affect the permeability coefficient in the field.

4.5 Freeze-Thaw Test

Samples were subjected to freeze-thaw testing according to ASTM C666, in which the samples are frozen and thawed in the wet condition. To simulate potential Maryland field conditions, two other tests were performed. A dry, hard freeze with zero saturation was conducted and specimens with 50% saturation were also tested. The 50% saturation was to mimic the potential for clogging in the field. The molded prisms were removed from the curing box and wiped clean. Each prism was weighed and recorded. The prisms were then placed in the freeze-thaw machine and the appropriate water level was added. For the fully saturated prisms, the water level reached over the top of each specimen. The machine was started and set to a maximum of 6 cycles per day. At the end of 30 cycles, the specimens were allowed to thaw. Each specimen was then removed from the freeze-thaw machine and weighed. Once all the specimen weights were recorded, the housing compartment was drained and cleaned. Each specimen was then placed back in the freeze-thaw machine. Each specimen's location was shifted one place per ASTM C666. Correct water amounts were added to the prisms and the machine was then turned on. The test was complete when a sample reached 300 cycles or 15% mass loss. Test #1 was the fully saturated sample. Test #2 was the sample with 50% saturation. Test #3 was the dry freeze with zero saturation.

Figure 4.8: Specimens in Freeze-Thaw Chamber

Tables 4.9-4.18 contain the results for the 300 cycles.

Table 4.9: Freeze-Thaw at 30 Cycles

Date of Test	10/6/2010	Cycles = 30		Percent remaining
	Control Test 1	3715	g	96.9
	Control Test 2	3606	g	96.0
	Control Test 3	3808	g	97.1
	Delayed Set Modifier Test 1	3850	g	97.1
	Delayed Set Modifier Test 2	3758	g	96.3
	Delayed Set Modifier Test 3	3870	g	97.0
	Viscosity Modifier Test 1	3666	g	97.0
	Viscosity Modifier Test 2	3545	g	97.0
	Viscosity Modifier Test 3	3701	g	97.1
	Cellulose Fiber Test 1	3977	g	99.0
	Cellulose Fiber Test 2	4002	g	98.8
	Cellulose Fiber Test 3	4078	g	99.0

Table 4.10: Freeze-Thaw at 60 Cycles

Date of Test	10/11/2010	Cycles = 60		Percent remaining
	Control Test 1	3523	g	91.9
	Control Test 2	3606	g	96.0
	Control Test 3	3763	g	96.0
	Delayed Set Modifier Test 1	3647	g	92.0
	Delayed Set Modifier Test 2	3744	g	96.0
	Delayed Set Modifier Test 3	3790	g	95.0
	Viscosity Modifier Test 1	3477	g	92.0
	Viscosity Modifier Test 2	3504	g	95.9
	Viscosity Modifier Test 3	3657	g	95.9
	Cellulose Fiber Test 1	3850	g	95.8
	Cellulose Fiber Test 2	3969	g	98.0
	Cellulose Fiber Test 3	4037	g	98.0

Table 4.11: Freeze-Thaw at 90 Cycles

Date of Test	10/16/2010	Cycles = 90		Percent remaining
	Control Test 1	3245	g	84.6
	Control Test 2	3450	g	91.8
	Control Test 3	3690	g	94.1
	Delayed Set Modifier Test 1	3305	g	83.3
	Delayed Set Modifier Test 2	3587	g	91.9
	Delayed Set Modifier Test 3	3762	g	94.3
	Viscosity Modifier Test 1	3223	g	85.3
	Viscosity Modifier Test 2	3356	g	91.8
	Viscosity Modifier Test 3	3579	g	93.9
	Cellulose Fiber Test 1	3609	g	89.8
	Cellulose Fiber Test 2	3840	g	94.8
	Cellulose Fiber Test 3	3997	g	97.0

Table 4.12: Freeze-Thaw at 120 Cycles

Date of Test	10/21/2010	Cycles = 120		Percent remaining
	Control Test 1	0	g	0.0
	Control Test 2	3380	g	90.0
	Control Test 3	3688	g	94.1
	Delayed Set Modifier Test 1	0	g	0.0
	Delayed Set Modifier Test 2	3511	g	90.0
	Delayed Set Modifier Test 3	3746	g	93.9
	Viscosity Modifier Test 1	0	g	0.0
	Viscosity Modifier Test 2	3299	g	90.3
	Viscosity Modifier Test 3	3545	g	93.0
	Cellulose Fiber Test 1	3569	g	88.8
	Cellulose Fiber Test 2	3770	g	93.0
	Cellulose Fiber Test 3	3981	g	96.6

Table 4.13: Freeze-Thaw at 150 Cycles

Date of Test	10/26/2010	Cycles = 150		Percent remaining
	Control Test 1	0	g	0.0
	Control Test 2	3302	g	87.9
	Control Test 3	3652	g	93.1
	Delayed Set Modifier Test 1	0	g	0.0
	Delayed Set Modifier Test 2	3456	g	88.6
	Delayed Set Modifier Test 3	3729	g	93.5
	Viscosity Modifier Test 1	0	g	0.0
	Viscosity Modifier Test 2	3164	g	86.6
	Viscosity Modifier Test 3	3555	g	93.2
	Cellulose Fiber Test 1	3410	g	84.9
	Cellulose Fiber Test 2	3706	g	91.5
	Cellulose Fiber Test 3	3941	g	95.6

Table 4.14: Freeze-Thaw at 180 Cycles

Date of Test	10/31/2010	Cycles = 180		Percent remaining
	Control Test 1	0	g	0.0
	Control Test 2	3129	g	83.3
	Control Test 3	3648	g	93.0
	Delayed Set Modifier Test 1	0	g	0.0
	Delayed Set Modifier Test 2	3213	g	82.3
	Delayed Set Modifier Test 3	3705	g	92.9
	Viscosity Modifier Test 1	0	g	0.0
	Viscosity Modifier Test 2	3050	g	83.5
	Viscosity Modifier Test 3	3541	g	92.9
	Cellulose Fiber Test 1	0	g	0.0
	Cellulose Fiber Test 2	3669	g	90.5
	Cellulose Fiber Test 3	3933	g	95.4

Table 4.15: Freeze-Thaw at 210 Cycles

Date of Test	11/05/2010	Cycles = 210		Percent remaining
Control Test 1		0	g	0.0
Control Test 2		0	g	0.0
Control Test 3		3634	g	92.7
Delayed Set Modifier Test 1		0	g	0.0
Delayed Set Modifier Test 2		0	g	0.0
Delayed Set Modifier Test 3		3697	g	92.7
Viscosity Modifier Test 1		0	g	0.0
Viscosity Modifier Test 2		0	g	0.0
Viscosity Modifier Test 3		3526	g	92.5
Cellulose Fiber Test 1		0	g	0.0
Cellulose Fiber Test 2		3606	g	89.0
Cellulose Fiber Test 3		3910	g	94.9

Table 4.16: Freeze-Thaw at 240 Cycles

Date of Test	11/10/2010	Cycles = 240		Percent remaining
	Control Test 1	0	g	0.0
	Control Test 2	0	g	0.0
	Control Test 3	3616	g	92.2
	Delayed Set Modifier Test 1		g	0.0
	Delayed Set Modifier Test 2		g	0.0
	Delayed Set Modifier Test 3	3685	g	92.4
	Viscosity Modifier Test 1		g	0.0
	Viscosity Modifier Test 2		g	0.0
	Viscosity Modifier Test 3	3509	g	92.0
	Cellulose Fiber Test 1		g	0.0
	Cellulose Fiber Test 2	3404	g	84.0
	Cellulose Fiber Test 3	3906	g	94.8

Table 4.17: Freeze-Thaw at 270 Cycles

Date of Test	11/15/2010	Cycles = 270		Percent remaining
	Control Test 1	0	g	0.0
	Control Test 2	0	g	0.0
	Control Test 3	3608	g	92.0
	Delayed Set Modifier Test 1	0	g	0.0
	Delayed Set Modifier Test 2	0	g	0.0
	Delayed Set Modifier Test 3	3664	g	91.9
	Viscosity Modifier Test 1	0	g	0.0
	Viscosity Modifier Test 2	0	g	0.0
	Viscosity Modifier Test 3	3495	g	91.7
	Cellulose Fiber Test 1	0	g	0.0
	Cellulose Fiber Test 2	0	g	0.0
	Cellulose Fiber Test 3	3887	g	94.3

Table 4.18: Freeze-Thaw at 300 Cycles

Date of Test	11/20/2010	Cycles = 300		Percent remaining
	Control Test 1	0	g	0.0
	Control Test 2	0	g	0.0
	Control Test 3	3585	g	91.4
	Delayed Set Modifier Test 1	0	g	0.0
	Delayed Set Modifier Test 2	0	g	0.0
	Delayed Set Modifier Test 3	3610	g	90.5
	Viscosity Modifier Test 1	0	g	0.0
	Viscosity Modifier Test 2	0	g	0.0
	Viscosity Modifier Test 3	3416	g	89.6
	Cellulose Fiber Test 1	0	g	0.0
	Cellulose Fiber Test 2	0	g	0.0
	Cellulose Fiber Test 3	3856	g	93.6

Test #1, 100% fully saturated samples showed the quickest deterioration of the samples, followed by Test #2, 50% saturation. The hard dry freeze, Test #3, with zero saturation had the least deterioration of all the samples. The cellulose fiber samples had the least deterioration among all four tests. Rapid deterioration was seen among all the samples once the percent remaining was below 90%. Once the samples lost more than 10% of their original mass, rapid deterioration was eminent. Figures 4.9-4.11 contain the graphical results of percent remaining for Test #1, Test #2, and Test #3 respectively.

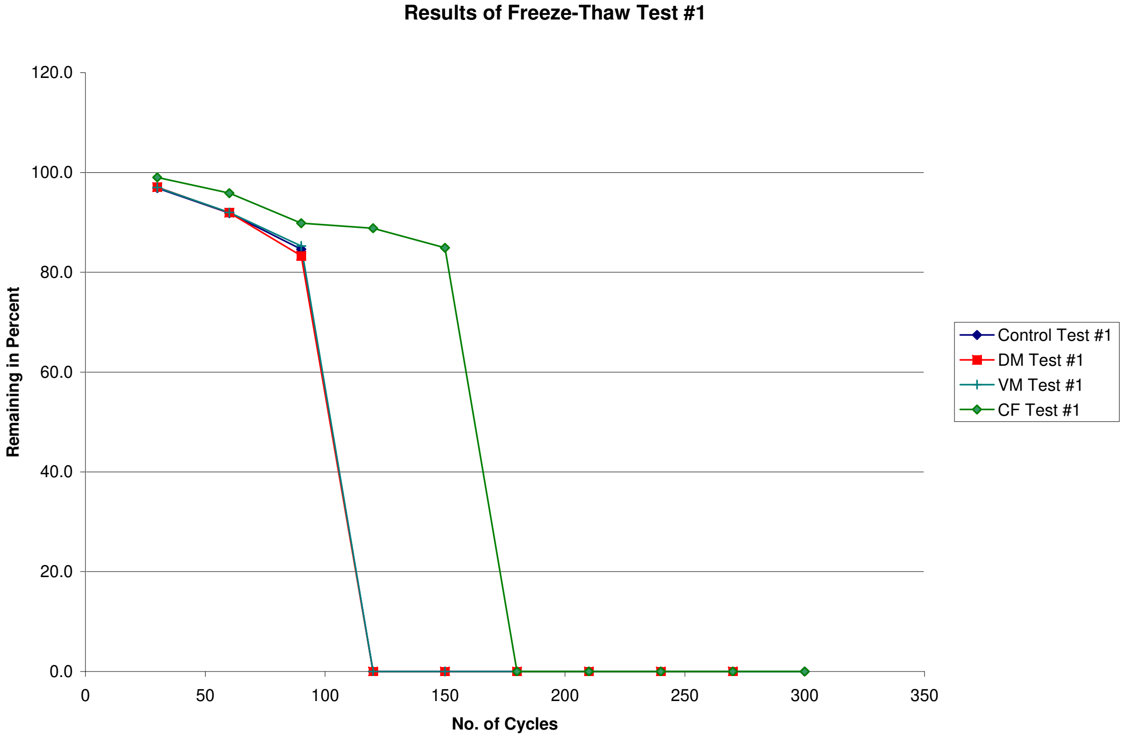


Figure 4.9: Graph Results for Fully Saturated Samples (Test #1)

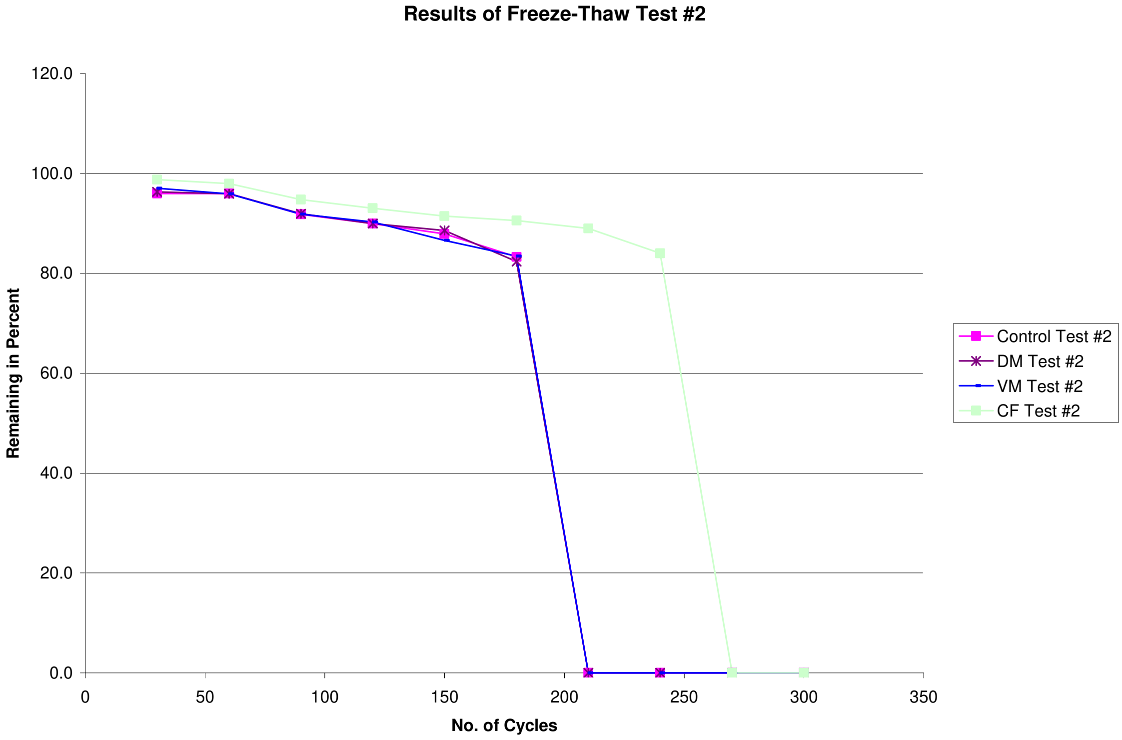


Figure 4.10: Graph Results for 50% Saturated Samples (Test #2)

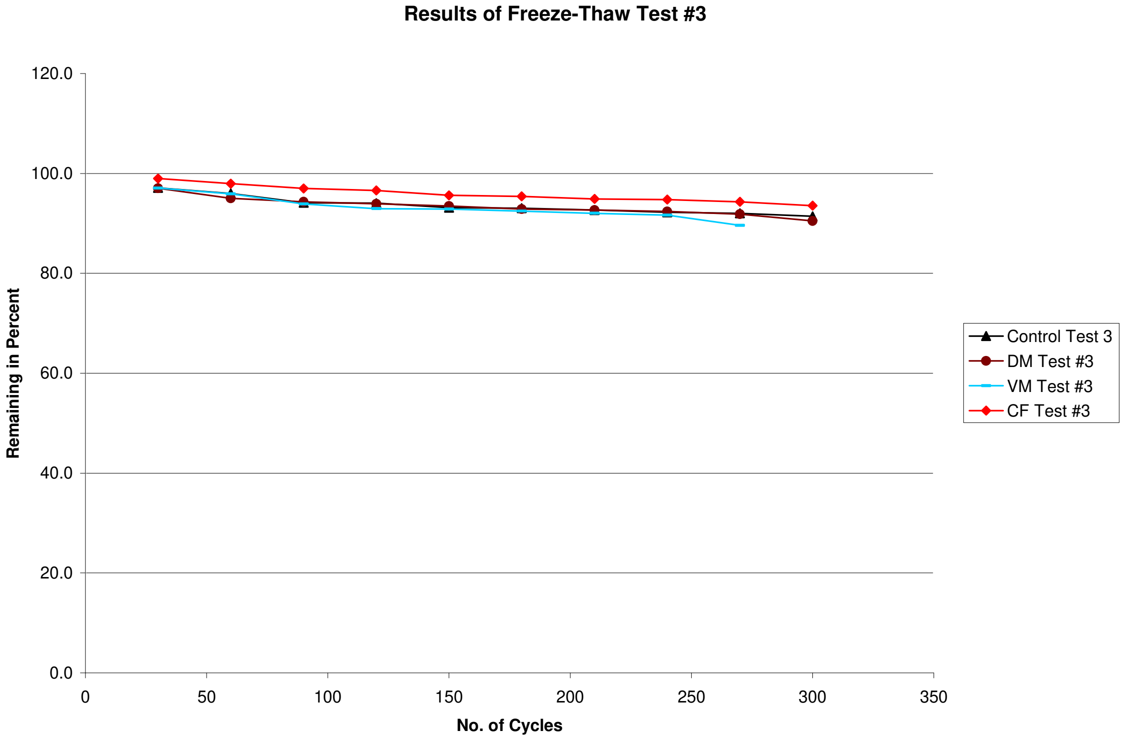


Figure 4.11: Graph Results for 0% Saturated Samples (Test #3)

4.6 Abrasion Test

The abrasion resistance was measured through the standard test method described in ASTM C944. This test determined the abrasion resistance by measuring the amount of concrete abraded off a given surface by a rotating cutter for a given time period. The rotating cutter has specific dimensions and other requirements. The drill bit was borrowed from a U.S. Department of Transportation research facility and the test was conducted at Eastern Testing and Inspection Laboratory in Frederick, Maryland. The rotating cutter was comprised of a series of wheels mounted on a sphere. The cutter was then attached to a standard drill bit which can fit most standard drills. Per the ASTM C944 standard, the drill press rotated at 200 revolutions per minute and applied a constant force of 22 pounds to the surface of the specimen. The cylinders used were 6 in. diameter which allowed the 3.25 in. diameter drill bit enough surface area for contact. Specimens were removed from the curing box after 28 days and wiped clean with a dry towel. The cylinder was then weighed and the weight recorded. The drill bit was cleaned and attached to the drill. The cylinder was then placed on the drill bench and locked in place with three wooden clamps. The drill was turned on and allowed to remain in contact with the top surface of the pervious concrete sample. At the end of two minutes, the drill was turned off and the specimen was cleaned and brushed. The weight was then measured and recorded. Once all the debris was removed and the weight recorded, a second round of abrasion test was performed. After two minutes, the specimen was cleaned and weighed.

Figure 4.12: Surface Abrasion Test

It was noted that during testing, the rotary cutter continued to vibrate vertically by a small factor. While there was constant contact between the rotary cutting dressing wheel and the pervious concrete sample, the overall test seemed slightly difficult to control consistently for all samples. While the abrasion loss appears to be approximately constant, the cellulose fiber specimens exhibited the least amount of abrasion loss for both applied loads. The results can be seen in Table 4.19.

Table 4.19: Results for Abrasion Test

ASTM C944		Applied Load #1	Applied Load #2
Date of Test	11/26/2010	Percent Mass Loss	Percent Mass Loss
	Control Mix 1	0.2 %	0.5 %
	Control Mix 2	0.3 %	0.5 %
	Delayed Set Modifier 1	0.4 %	0.6 %
	Delayed Set Modifier 2	0.3 %	0.6 %
	Viscosity Modifier 1	0.3 %	0.5 %
	Viscosity Modifier 2	0.3 %	0.5 %
	Cellulose Fiber 1	0.1 %	0.3 %
	Cellulose Fiber 2	0.1 %	0.3 %

Abrasion resistance of pervious concrete is a concern at locations where there is significant turning traffic or locations that will need snow plows. This is based on the researcher's test results and other independent research. Due to the low w/c ratio of pervious concrete, there is a significant increase in surface drying and potential raveling of the aggregates.

Chapter Five

Discussion of Results

5.1 Overview

The results of the three different admixtures are discussed in this chapter. Observations noted during mixing and sample preparations, as well as test results are discussed.

5.2 Delayed Set Modifier Results

With the low water-to-cement ratio for pervious concrete, the hydration of the cement is considered to flash. This speeds up the hydration of the cement and lowers the amount of allowable time for transport. While the delayed set modifier is helpful in field applications, the structural and durability effects on the pervious concrete pavement are minimal.

During mixing and sample preparation, it was noted that the mix seemed more fluid than the control mix. When discharging from the mixer, the mix poured out easily. Taking a small sample and balling it up, the cement paste did adhere slightly to the glove. While this method is subjective, it is currently being used by some for checking consistency in a pervious concrete mix. After the mix was placed in molds and cured for one day, the specimens were then removed from their molds. It was noted that some specimens had a thin layer of paste formed at the bottom of the cylinders. This could have been caused by over compaction of the specimens in the cylinder molds. Another explanation could also be the chemical reaction of the delayed set modifier with the cement.

Based on the product data sheet supplied by WR Grace, the delayed set modifier contained both lignosulfate acids and hydroxylated carboxylic acids. These two acids slow down the hydration process by inhibiting the chemical reaction of cement to water. This is achieved by allowing the delayed set modifier to form a thin film around the cement compounds. The thickness of this film is directly correlated to the amount of retarding in the mix. While conventional concrete has more of a tolerance to potential over-dosage of delayed set modifier, pervious concrete is more susceptible. With the low water-to-cement ratio, an over dosage of delayed set modifier will stop the hydration of cement at a certain stage. By not allowing the cement paste to set around the aggregates, the cement settles at the bottom and dries. This creates a less pervious layer. It is important to note that at the time of mixing, there were not any set guidelines for dosage rates in pervious concrete pavements.

The density and void content of the delayed set modifier was slightly higher than the other three mixtures. This could have been attributed to the formation of the thin layer around the cement and aggregate. With a more fluid material discharging from the mixer, this created less paste and more open voids.

The compressive strength showed the delayed set modifier had the highest strength gained for the 7, 14, and 120 day tests. This could be attributed to the lower water to cement ratio that was achieved. As the delayed set modifier reacts with the cement, this lowers the demand on the water needed to complete the reaction. Lower w/c ratio increases the compressive strength. The 28 day strength, however, was significantly lower than the other three admixtures. The samples taken at 28 days could have had more of an open voided structure due to the excess paste that did not form and hydrate around the aggregates.

5.3 Viscosity Modifier Results

The viscosity modifying admixture (VMA) created a more workable and easier to mold mix. This is due to the presence of high molecular weight polymers that interact with the water/cement. The density and void content were comparable to the control mix. This is to be expected. The VMA had little effect on the properties of fresh concrete.

When the cylinders were removed from their molds, it was noted that some of the specimens had a small impermeable film of cement paste on the bottom. This could be due to either over compaction of the concrete specimens or the excessive reaction of VMA with cement. If a high dosage rate of VMA is specified, this can have an adverse effect on the setting time. This allows the cement paste to remain in a more fluid-like state longer, allowing gravity to pull the cement paste to the bottom of the cylinder and harden.

The viscosity modifying admixture resulted in relatively low compressive and tensile strength. Day 7 and day 14 had the lowest compressive strength compared to compressive strength of specimens with other admixtures. This may be explained by the high dosage rate of the viscosity modifying admixture used in the previous concrete mix design. The tests for permeability, freeze-thaw, and abrasion had average results; the recorded results were in line with the control mix.

5.4 Cellulose Fiber Results

Not surprisingly, cellulose fibers had an important impact on the durability of pervious concrete. Although the traditional polypropylene fibers have shown great promise in pervious concrete, it was unclear how the cellulose fibers would compare. The wet mix was very comparable to the control mix. The ease at which the pervious concrete was removed from the mixer and molded was very similar to the control mix. This was to be expected since the fibers did not affect the overall chemical properties of the cement. The use of small fibers also helped in reducing the problematic issue of fibers balling in the mix.

The results of the compressive strength were also very similar to the control mix. The greater advantage of the cellulose fibers came from the tensile strength and the freeze-thaw test. The tensile strength for the cellulose fibers had the highest reported value as expected. The addition of cellulose fibers to the cementitious material stiffens the matrix. This stiffening not only reduces the cracking due to both plastic and drying shrinkage, but also helps with ductility. The fibers help bridge the gap between aggregates and create a strong matrix of interwoven cellulose fibers.

The freeze-thaw resistance was the highest of all the mixes, providing a very strong resistance. The fibers played a very strong role is resisting the thermal expansion and contraction due to the repetitive freezing and thawing. Regardless of the type of test (dry, 50% saturated, 100% saturated), the cellulose fiber mix had the least amount of mass loss.

Chapter Six
Conclusions

6.1 Summary

Although limited in its applications, pervious concrete has the potential to help mitigate many of the urban stormwater quality issues. Lack of extensive research on pervious concrete has led to some misunderstanding and narrow focus on the use of pervious concrete. One of the objectives of this research was to develop a preliminary pervious concrete specification for Maryland conditions. Several admixtures have been tested as part of this research with the objective of increasing strength, durability and workability of pervious concrete. Improved strength, durability and workability would lead to a wider application of pervious concrete.

The types of admixtures that were tested as part of this research included delayed set modifier, viscosity modifier, and cellulose fibers. These three admixtures were selected based on the potential of increasing strength, durability, workability, or a combination of the three.

The ability to discharge, place, and finish pervious concrete within a relatively short time span is a major concern for concrete producers. The relatively short working time window with pervious concrete often leads to a very fast paced, labor intensive effort. Incorporating a delayed set modifying admixture into the pervious concrete mix design inevitably allows a longer working window for placement.

Pervious concrete is a harsh mix because it contains little or no fine aggregates. Viscosity modifiers have been developed to add body and help lubricate pervious concrete mixes. Better discharge and easier placement and compaction of an otherwise dry, harsh mix have been the key benefit with using VMA's. Viscosity modifiers alter the rheology, or flow behavior, of a concrete mix; each VMA can have a differing effect on the mix based on its specific chemistry. Some VMAs have been used in pervious concrete with less than desirable results. Certain VMAs work by binding water in a concrete mix, thereby changing its viscosity.

Cellulose fibers have been gaining popularity as an alternative for polypropylene fibers. It is a green product and has been gaining a lot of attention. Modern cellulose fibers are based upon a virgin, purified form of the cellulose fiber. Cellulose fibers have some significant advantages in addition to being a renewable source of material. They contribute to reduction in shrinkage and temperature cracking, and fiber balling. There are also a few drawbacks. One of the major drawbacks is that the fibrous pulps are not resistant to alkaline or other fungi and algae attacks. To help prevent this and strengthen the cellulose fibers, the outer surfaces of each fiber are coated and treated with a biocide material. This biocide material is an alkaline resistant coating that does not impede the bonding of the cement paste to the fiber.

The type of testing selected was to determine the effect the three admixtures had on increasing durability while maintaining a standard level of structural performance. Density and void ratio test has been one of the few tests that has been widely accepted and used in the industry. This test helps to determine if the freshly mixed concrete will achieve the targeted void content as specified in the mix design. The test was conducted at the University of Maryland. The density and void content was found by first determining the theoretical density of the concrete computed on an air-free basis. The absolute volumes were determined by taking the quotient of the mass of the ingredient divided by the product of its relative density times the density of water. To calculate the actual mix density, the mass of the concrete filled container must be subtracted from the mass of the container and then divided by the volume of the container. The target void content of the mix design was 20%.

The compressive strength was measured on all samples at 7, 14, 28, and 120 days of curing. The tests were designed to determine the rate of strength gain of all the specimens. The compressive strength tests were conducted at the University of Maryland.

The split cylinder test was conducted on all samples. Tensile strength is an important characteristic of pavements. The tensile strength of a pervious concrete sample was measured by compressing a cylinder through a line load applied along its length. This test was completed in a standard compression testing machine. The test was conducted on the same machine used for compression tests at the University of Maryland.

Permeability is probably the most critical property in a pervious concrete design. It was important to maintain a high degree of permeability in all samples while trying to enhance other factors. The falling head test method was used. An apparatus was built and the specimens were tested at the Eastern Testing and Inspection Laboratory in Frederick, Maryland.

With the rapid freeze-thaw cycles that are common in Maryland, freeze-thaw durability was considered to be an important property for pervious concrete applications in Maryland. Three different types of tests were conducted: dry hard freeze with zero saturation, 50% degree of saturation, and 100% degree of saturation. The tests were conducted in a freeze-thaw chamber at the University of Maryland.

Abrasion test was the final test conducted on the previous concrete samples. This test determined the abrasion resistance by measuring the amount of concrete abraded off a given surface by a rotating cutter for a given time period. The drill bit was borrowed from a U.S. Department of Transportation research facility and the tests were conducted at the Eastern Testing and Inspection Laboratory in Frederick, Maryland. The rotating cutter comprised of a series of wheels mounted on a sphere. The cutter was attached to a standard drill bit which can fit most standard drills.

6.2 Findings

The important characteristic that needed to be maintained was a proper void ratio within the pervious concrete mixture. Sacrificing permeability for an increase in strength or durability was not seen as a viable option. Therefore, the target void ratio for the different mix designs was a standard 20%. This is an accepted void ratio that allows for adequate amount of free draining through the pervious concrete. Of the three types of admixtures tested, cellulose fibers had the greatest impact on durability. The aggregate-paste matrix was held together by a strong bond with the fibers. The strong bond increased the freeze-thaw durability as well as the abrasion resistance.

The delayed set modifier did appear to result in a more fluid mix. However, the chemical reaction that occurred between the delayed set modifier and the cement partially inhibited the formation of cement around the coarse aggregates. By delaying the set time of the cement, it allowed gravity to pull down the cement paste and resulted in a less pervious layer at the bottom of the cylinders in some instances.

The viscosity modifier resulted in little change in strength or durability. However, the mix was easier to move and mold into shape.

6.3 Recommendations

While much of the results of this research suggest the potential for expanding the application of pervious concrete, there are still other areas that need to be studied and evaluated. The amount of compaction a pervious concrete sample receives can influence much of its structural properties. Void ratio, permeability, and compressive strength are all directly correlated to the amount of compaction. Compaction methods vary greatly when it comes to placing pervious concrete in the field. A non-destructive test to determine the level of compaction as well as the uniformity of compaction throughout the sample would be helpful. The use of a non-destructive test like ultrasonic testing to determine a correlation between the results of the test and the actual in place measurement of compaction could prove beneficial for determining the structural properties of the in-place pervious concrete. Other non-destructive test methods could be reviewed and compared to find one that is suitable for previous concrete.

As pervious concrete becomes more applicable to light and medium traffic loading, the need for a fatigue analysis is going to become important. Much of the applications for pervious concrete involve parking lots, pedestrian walkways, and other lightly loaded areas. To be able to incorporate pervious concrete in wider applications, fatigue analysis will be needed.

Typical methods of construction for pervious concrete include the need to cover the pervious concrete pavement after placement to ensure moisture is not lost and that the cement paste fully cures. Fully saturating the aggregates in the pervious concrete mix design could potentially release moisture in a more controlled manner to the cement paste as hydration proceeds.

Pervious concrete is a green material but it does consume natural resources. Using recycled aggregates in pervious concrete could be another added environmental benefit. Concrete recycling is gaining popularity since it reduces the need for consuming natural resources as well as waste disposal. Several factors that play a pivotal role in the quality of recycled aggregates are size, type, and gradation of aggregates. These factors can affect the overall structural performance as well as permeability of pervious concrete. Various types, sizes, and gradation of recycled aggregate in pervious concrete could be studied to determine optimal recycled aggregate mixes.

Appendix A: Pervious Concrete Specifications and Commentary - DRAFT

Specification

1 General Requirements

1.1 Scope

1.1.1 The work described by this guide includes the installation and construction, including all labor, materials, and equipment necessary for construction of pervious concrete pavements. All work shall conform to the plans, specifications, and other documents for streets, parking lots, driveways, paths, walkways, and other pedestrian areas.

1.2 References

1.2.1 American Concrete Institute (ACI)

1. ACI 211.3R “Guide for Selecting Proportions for No-Slump Concrete”
2. ACI 305 “Hot Weather Concreting”
3. ACI 306 “Cold Weather Concreting”
4. ACI 522 “Report on Pervious Concrete”
5. ACI 522.1-08 “Specification for Pervious Concrete Pavement”
6. ACI Flatwork Finisher Certification

Commentary

1 General Requirements

1.1 Scope:

The commentary discusses and elaborates on some of the items mentioned in the specifications. Comments in the commentary are used to explain or provide additional information. The commentary is not intended to give a historical background or provide a complete background concerning sections covered in the specifications. The intention is to highlight and provide supplemental information.

1.2 References

Specification **Commentary**

Program

7. ACI Field Technician Program

1.2.2 American Society for Testing and Materials

1. ASTM C29 “Test for Unit Weight and Voids in Aggregate”
2. ASTM C33 “Specifications for Concrete Aggregate”
3. ASTM C42 “Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete”
4. ASTM C94 “Specification for Ready-Mixed Concrete”
5. ASTM C117 “Test Method for Material Finer than 200 Sieve in Mineral Aggregates by Washing”
6. ASTM C138 “Test Method for Unit Weight, Yield, and Air Content of Concrete”
7. ASTM C150 “Specifications for Portland Cement (Type I or II only)
8. ASTM C172 “Practice for Sampling Freshly Mixed Concrete”
9. ASTM C260 “Specification for Air-Entraining Admixtures for Concrete”
10. ASTM C494 “Specification for Chemical Admixtures for Concrete”
11. ASTM C595 “Specification for

Blended Hydraulic Cements”

12. ASTM C618 “Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete”
13. ASTM C989 “Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars”
14. ASTM C1077 “Practice for Laboratories Testing Concrete and Concrete Aggregate for Use in Construction and Criteria for Laboratory Evaluation”
15. ASTM C1116 “Specification for Fiber-Reinforced Concrete and Shotcrete”
16. ASTM C1157 “Performance Specification for Hydraulic Cement”
17. ASTM C1688 “Test Method for Density and Void Content of Freshly Mixed Pervious Concrete”
18. ASTM C1701 “Test Method for Infiltration Rate of In Place Pervious Concrete”

1.2 Submittals

1.2.1 Product Data

1. The contractor shall submit to the

1.2 Submittals

By supplying the architect/engineer of record with the proper materials to be

Specification

architect/engineer product data on cement, coarse aggregate, fine aggregate, joint filler, joint sealers, admixtures, and other relevant materials used.

1.2.2 Concrete Mix Design

1. The contractor shall submit to the architect/engineer proposed concrete mixture proportions including all material weights, volumes, density, water/cement material ratio, and void content with applicable graphs indicating concrete strength at 28 days.

1.2.3 Project Details

1. Contractor shall submit proposed jointing plans, details, schedule, construction procedures, and quality control plan to the architect/engineer.

1.2.4 Operation and Maintenance

1. Contractor shall submit a written preventative maintenance plan for clogging of the pervious pavement. The plan shall include periodic in-place testing for porosity and proposed methods to restore porosity if the rate falls below 75% of the original rate.

1.3 Quality Control

Commentary

used along the with mix design, this allows the design professional to accurately review and comment. Locally available materials approved by SHA should be used and submitted. The product data should list all the relevant properties of the materials including specific gravity and water absorption. The concrete mix design should indicate the anticipated void ratios, permeability rates, and a minimum compressive strength required to be achieved. The mix design should include aggregate gradation to ensure a proper average size for the aggregates.

Proper jointing is critical for pervious concrete pavements. Careful selection and location of joints will provide a better overall performance for pervious concrete as well as reduce the potential for plastic shrinkage and surface raveling.

1.3 Quality Control

Specification	**Commentary**
1.3.1 Prospective Bidders/Contractors 1. The bidder/contractor shall submit evidence of successful pervious concrete pavement projects including the project name and address and testing results. 2. The bidder/contractor shall have successfully completed the NRMCA Pervious Concrete Contractor Certification Program. The contractor, technicians, and skilled laborers are required to have the appropriate ACI Certifications prior to performing pervious concrete installations.	Placement and finishing are quite different for pervious concrete pavements compared to conventional concrete pavements. If strict guidelines are not followed, structural and hydrological properties can be affected. Therefore, it is recommended that placement of pervious concrete be limited to those with successful past experience. If the contractor has not demonstrated successful experience, an experienced consultant is recommended to supervise the base preparation, production, placement, finishing, and curing of the pervious concrete pavement.
1.3.2 Test Panels 1. Two test panels are to be placed, jointed, and cured to demonstrate to the Architect/Engineers satisfaction that in-place weights and permeability can be achieved at the site location. Each test panel is to be a minimum of 225 sq. ft. and at the required project thickness. 2. Test panels shall have acceptable surface finish, joint details, thickness, and porosity. Curing procedures shall conform to the Execution section of this	The use of test panels has been an important tool for pervious concrete pavements in other states. Not only does this allow the contractor to demonstrate his capabilities for installing pervious concrete, this also has the added benefit of verifying whether the site has proper compaction and drainage.

Specification **Commentary**

specification.

3. Satisfactory performance of the test panel shall be determined by:
    a. Compacted thickness no less than 1/4 inch of specified thickness.
    b. Void Structure ± 5%.
    c. Unit Weight ± 5 pcf of the design unit weight.

If the test panels are found to be unsatisfactory, the test panel shall be removed at the Contractors expense and disposed off in an approved landfill or recycling facility.

4. If the test panels have met the satisfactory performance mentioned above, the test panel can then be left in-place and included in the completed work.

1.3.3 Weather Limitations

1. The contractor shall not place pervious concrete for pavement when the ambient temperature is predicted to be lower than 40°F or higher than 90°F during the seven days following placement.
2. Pervious Concrete shall not be placed on frozen coarse aggregate or subgrade.
3. Evaporation control measure shall

Specification

be applied to the pervious concrete pavement at the time of placement until covering with sheeting.

2 Products

2.1 Sub-base

2.1.1 Subgrade Permeability - Storm water Detention Layer or Groundwater Recharge Bed

1. Testing to determine the subgrade soil infiltration rate shall be conducted by a qualified testing laboratory, by either the field or laboratory methods listed below:
2. Field Methods – ASTM D3385, ASTM D5093, or ASTM D 6391
3. Laboratory Methods – ASTM D5084 or ASTM D2434
4. The subgrade shall have a minimum infiltration rate of 0.50 in/hr.

2.1.2 Subgrade Support

The subgrade shall be compacted by a mechanical vibratory compactor to a minimum density of 95% of the maximum dry density as established by ASTM D698 or AASHTO T99. Subgrade permeability is inversely proportional to compaction so care should be taken to avoid compaction levels that prevent the subbase from providing the required permeability rates.

Commentary

3 Products

2.1 Sub-base

Prior to any work on the site, the subgrade permeability should be tested and checked for performance. If a minimum permeability is not reached in the subbase, this can have drastic effects on the pervious pavement design. Any problems will then be addressed and remedied as appropriate, either under the general contractor, the pervious concrete installer, or a registered professional engineer. It is recommended that existing roots, wood, stumps, sod, etc. be removed prior to installation of the previous concrete pavement.

Specification

2.2 Concrete

2.2.1 Concrete Mix Design

Contractor shall furnish a proposed mix design with proportions of materials to the Architect/Engineer prior to commencement of work. The data shall include unit weights, concrete break results, graphs, and other pertinent material deemed necessary. Mixture performance will be affected by properties of the particular materials used. Trial mixtures must be tested to establish proper proportions. General mixture proportions are as follows:

1. Aggregate/Cementitious ratio: 4:1 to 5:1
2. Concrete mixture unit weight: 120 lbs/cf
3. Concrete void content: 20% to 30%
4. W/c Ratio: .25 to .35

2.2.2 Cement: Portland cement Type I or II conforming to ASTM C150

2.2.3 Aggregates

1. Coarse aggregates shall meet the size and grading requirements defined in ASTM D448 and shall comply with ASTM C33. Fine aggregate, if used, shall not exceed

Commentary

2.2 Concrete

Locally available materials having a consistent record of successful use in pervious concrete mix deigns and approved by SHA shall be used. Past research has shown limestone to be the preferred choice. River gravel lacks the characteristics of limestone and has reduced strength and bonding characteristics with the paste. There have been many studies done on the effects of aggregate size. Smaller aggregates increase strength but adversely affect permeability. Larger aggregates have the direct opposite effect. While there have been some studies done on recycled aggregates in pervious concrete, there are still many more questions surrounding the use of recycled aggregates in pervious concrete. Recycled aggregates can also vary greatly in their chemical composition. Only those recycled aggregates approved by SHA should be used, if at all.

It is recommended that limited amounts of fine aggregates be used in the pervious concrete mix design. Fine aggregates have proven in numerous

Specification

3 cubic feet per cubic yard.

2. Larger aggregate sizes may increase porosity but can decrease workability. Well graded aggregates should be avoided as this has an impact on the porosity of the pavement.

2.2.4 Fly Ash

1. The use of fly ash in pervious concrete pavements shall conform to ASTM C618 and shall not exceed 20% of the total cementitious material.

2.2.5 Admixtures

1. Air entraining admixtures shall conform to ASTM C989.
2. Water Reducing Admixtures shall conform to ASTM C494.
3. Retardants shall conform to ASTM C494.
4. Viscosity Modifying Admixtures (VMA’s).

2.2.6 Fiber Reinforcement

1. Cellulose fibers shall be in accordance with ASTM C1116 made of natural fibers conforming to ASTM D 7357.

2.2.7 Water

1. Water shall be potable and comply with ASTM C1602.

Commentary

studies and research to greatly increase strength while slightly decreasing permeability. The free moisture content of the fine aggregates should be determined by the supplier and be within 0.5% accuracy. With the low w/c ratio in pervious concrete, higher percentages have been shown to not perform as well. Replacement of cement with fly ash also provides improved placing and finishing characteristics including improved workability of the low slump mix. This is a major benefit, particularly when surface texture and design concerns are of high priority.

Admixtures are an important aspect of pervious concrete. With a harsh and dry mix, admixtures help in achieving a more acceptable mix and help with batching, transporting, and placing. Amounts and ratios should be adjusted due to the low water-to-cement ratio in pervious concrete. The three most common admixtures used in pervious concrete are high range water reducers, viscosity modifiers, and hydration stabilizers. While these are typically used in conventional concrete, the

Specification

Commentary

dosage rate can vary significantly when used in pervious concrete due to the difference in material quantities.

While there are a variety of fibers available, cellulose fibers with an alkali resistant coating have shown the greatest potential in pervious concrete. Polypropylene fibers have been commonly used in conventional slabs but not in pervious concrete. Made from natural materials, cellulose fibers offer a greener solution. Microfibers in the pervious concrete mix have been shown to increase freeze-thaw resistance, limit early age plastic shrinkage, and increase tensile capacity. An application rate of 1.5 lbs/cubic yard is recommended for adequate dispersion. While dosage rates as high as 4.0 lbs/cubic yard have been used, there was little added benefit for this additional fiber content.

Specification

2.3 Jointing

2.3.1 Isolation joint materials shall comply with ASTM D 994, D1751, or D1752.

2.4 Forms

2.4.1 Forms shall be made of reinforced plastic or steel. Wood, if used, should be used sparingly.

3 Execution

3.1 Subgrade Preparation

3.1.1 Prepare subgrade as specified in the contract documents. The top 6 inches shall be composed of granular soil.

3.1.2 Subgrade is to be constructed as specified in the contract documents with the required minimum pavement thickness attained in all locations.

3.1.3 Compaction of the subgrade during construction must be monitored. Over compaction of the subgrade can affect the overall permeability of the pervious concrete pavement.

3.1.4 Place choker stone over top of the undisturbed subgrade as specified in the contract documents. Size,

Commentary

2.3 Jointing

2.4 Forms

4 Execution

3.1 Subgrade Preparation

Having a continuous uniform subgrade is a key element for placing pervious concrete. Irregularities should be smoothed out and the subgrade should be free from standing water. The introduction of water to the pervious concrete can have harmful effects. At the same time, the subgrade should not be overly dry either. A dry subgrade could draw water and moisture from the bottom surface of the pavement, thereby creating uneven drying. A layer of choker stone at the bottom surface of the pervious concrete pavement allows storage of rainwater if the subgrade becomes saturated and is unable to quickly drain and percolate.

Specification

type, and thickness of the subbase choker stone layer shall conform to the contract documents.

3.2 Formwork

3.2.1 Form Materials

1. Form materials shall be made of reinforced plastic or steel. Wood shall be used sparingly. Forms shall be placed for the full depth of the pavement and be of sufficient strength and stability to support mechanical equipment without deformation of plan profiles following spreading, strike-off, and compaction operations.
2. Forms shall have a removable spacer and be placed above the depth of the pavement. Spacers shall be removed following placement and vibratory strike-off to allow roller compaction.

3.2.2 Setting formwork

1. Set, align, and brace forms so that the hardened pavement meets the tolerances specified in the specification.

Commentary

Specifying the top 6 inches of the subbase with gravelly soil or some other form of easily permeating subbase also allows another level of storage for rainwater.

3.2 Formwork

Specification

2. Apply form release agent to the form face which will be in contact with concrete, immediately before placing concrete.
3. Placement widths shall be specified in the contract documents and shall not exceed 20 feet.

3.3 Mixing and Delivery

3.3.1 Mixing

1. Mixtures shall be produced in central mixers onsite or in trucks.
2. Concrete mixed in transit mixers shall be mixed at the speed designated by the manufacturer for 75-100 revolutions.

3.3.2 Transportation

1. The pervious concrete mixture may be transported or mixed onsite and discharge of individual loads shall be completed within one hour from the introduction of mix water to the cement. Delivery times may be extended to 90 minutes when a hydration stabilizer is used.

Commentary

3.3 Mixing and Delivery

Discharge time should be limited to a maximum of one hour. This will prevent early drying of the pervious concrete making it easier to discharge from the mixer.

Specification

3.4 Placing and Finishing

3.4.1 Placement

1. The contractor shall provide mechanical equipment of either slip form or form riding equipment to place the concrete. Internal vibration equipment is not allowed.
2. Place the pervious concrete pavement 1/2 inch to 3/4 inch above the final specified height.
3. The practice of discharging the pervious concrete onto bedding course and pulling or shoveling the pervious concrete into placement is not allowed.

3.4.2 Finishing

1. Once mechanical or other strike-off and compaction efforts have commenced, no other finishing operations shall be allowed.
2. Finish the pavement to the final elevations specified in the contract documents.

Commentary

3.4 Placing and finishing

The more common approach to placing pervious concrete is in forms on grade that have a riser strip on the top of each form. The pervious concrete will then be placed 3/8-1/2 in. (9 to 12 mm) above final pavement elevation. Pervious Concrete must be discharged as close to final position as possible and eliminate dragging or pumping. If wheelbarrows are used, enough time and help must be made available before the concrete hardens. During placement, the strike off or screed should be made at the proper final elevation. To form the edges, a1 ft x 1 ft steel tamp, a float, or other similar devices should be used. This will help prevent raveling along the edges. A steel roller is usually used to consolidate the pervious concrete pavement. Consolidation should happen fairly soon after screeding because of the rapid hardening and high evaporation. It is recommended that compaction occurs within 15 to 20 minutes of placement. Finishing

Specification

Commentary

the previous concrete is usually accomplished with the roller compaction. Floating and troweling operations tend to close up the top surface of the voids and should not be used. The final finish will be a rough surface.

3.5 Final Surface Texture

The final surface texture of pervious concrete is not tight and uniform. The surface should be open and varied.

3.5 Final Surface Texture

3.6 Curing

1. Curing should begin within 20 minutes of concrete discharge. The concrete pavement surface should be covered with a minimum of six-mil thick polyethylene sheet or other approved covering material.
2. Prior to covering, a light fog or mist shall be applied to the top surface of the pavement when required due to ambient temperatures.
3. The cover must be securely fastened to prevent dirt and other debris from becoming lodged in the pervious pavement surface.

Pavement shall be cured for a minimum of

3.6 Curing

Since previous concrete has an open voided surface, it is exposed to more evaporation. This makes curing even more critical than in conventional concrete. To help with this fast drying and curing time, it is common to apply an evaporation retarder before compaction to minimize any potential for surface water loss.

Pervious concrete pavements have a high probability for plastic shrinkage cracking due to the elimination of bleed water. The recommended practice for curing

Specification

7 days unless otherwise specified.

3.7 Jointing

Control joints shall be placed at a maximum of 40-foot intervals.
Joint depth shall be 1/4 of the pavement thickness and can be installed when the concrete is still in the plastic stage or saw cut once the concrete has hardened.

Commentary

pervious concrete is to have a mist or fog machine apply a light wet coat to the top surface of the newly finished pavement and then cover with a plastic sheet for a minimum of seven days.

3.7 Jointing

Since pervious concrete shrinks less than conventional concrete, control joints could be spaced at a greater distance. To help mitigate random cracking of pavements, control joints should be placed at 20 ft (6 m) with a maximum of 40 ft spacing. To prevent uncontrolled reflective cracking, joints should be installed at the same locations as the adjacent and adjoining pavement. The depth of the joints should be ¼ of the pervious concrete pavement thickness.

Installation of joints should occur soon after consolidation. A rolling tool has been frequently used and has been quite successful. While saw-cutting is possible, it is not a preferred method. The slurry from the sawing operations can

Specification

3.8 Testing, Inspection, and Acceptance

1. A qualified independent testing and inspection agency will perform field tests and inspections and prepare test reports. The concrete producer shall endorse the technicians testing proficiency of Portland Cement Pervious Concrete
2. A minimum of one test for each day's placement of pervious concrete in accordance with ASTM C172 and ASTM C29 to verify unit weight and 28 day compressive strength shall be conducted. The unit weight of the delivered concrete shall be ±5 pcf of the design unit weight.

Commentary

potentially clog and block voids in the pervious pavement.

3.8 Testing, Inspection, and Acceptance

REFERENCES

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