Research, Development
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District Department of Transportation

Evaluation of Mix Designs and Test Procedures for Pervious Concrete

Final Report

October 27, 2014

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Evaluation of Mix Designs and Test Procedures for Pervious Concrete

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DDOT

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16. Abstract

Pervious concrete is mixture of cement, aggregate, and water that provide a level of porosity which allows water to percolate into the sub-grade. It differs from the conventional concrete since it usually contains a smaller amount of fine aggregate. There is typically single size aggregate in pervious concrete which results in larger air void than conventional concrete. The District Department of Transportation (DDOT) constructed pavements in selected street alleys using pervious concrete on a pilot basis. DDOT does not currently have its own specifications for pervious concrete. As a result, this research was aimed at developing and testing five design mixes of pervious concrete to identify the appropriate mix which would provide the maximum compressive strength with an acceptable permeability rate and flexural strength. The tests were conducted on the five design mixes using three different types of compaction methods (self-consolidating, half-rodding and Standard Proctor Hammer). Based on the results, a design mix with a compressive strength of 3,500 pounds per square inch (psi) with a maximum coefficient of permeability of 57.82 inches per hour (in/hr) was selected. The maximum modulus of rupture of the selected mix was determined to be 565 psi. The in-situ infiltration tests conducted on at 3 locations in DC with the optimal pervious concrete mix yielded average infiltration rates between 86.1 and 208.7 in/hr. This falls within the typical infiltration rate of pervious concrete (i.e., 100 to 200 in/hr, on average).

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EXECUTIVE SUMMARY

The District Department of Transportation (DDOT) is committed to mitigating stormwater runoff and improving the water quality in the rivers of the metropolitan area. To this end a number of strategies have been developed or are under consideration, including the use of pervious concrete pavements. Pervious concrete is a mixture of Portland cement, aggregate, and water that provides a level of porosity that allows water to percolate into the subgrade. The general literature suggests that in addition to reducing the quantity of runoff water and improving water quality, pervious concrete could also enhance pavement skid resistance, especially during storm events by rapidly draining rainwater.

Quality control and quality assurance for job mix verifications and testing for pervious concrete is not covered in the Standard Specifications for Highways and Structures of the District of Columbia. It is also addressed by neither the American Society for Testing and Materials (ASTM) nor the American Association of State Highway and Transportation Officials (AASHTO). To address this gap, this study developed internal guidelines for quality control of field sampling and testing of pervious concrete mixes for acceptance. Additionally the study tested several mix designs to determine the optimum amount of fine aggregates that can be incorporated in to the mix design with minimal adverse effect on strength and permeability.

Five design mixes were prepared in June 2013 (including a control mix) and tested in the laboratory. The mixes had varying amounts of fine aggregates and some included micro fibers. The mixes were tested for compressive strength, permeability, porosity, percent voids, and flexural. Three sample preparation methods were used: a) self-consolidating also referred to as self-compacting, where the cylinder molds were filled to the top and excess concrete removed with a strike plate applying downward pressure; b) rodding per ASTM C 192 in 2 lifts and no tapping; and c) compacting with a standard Proctor Hammer, 2 lifts in 20 drops per lift.

The mix and the sampling method which yielded the optimum compressive strength and an acceptable coefficient of permeability and a significant flexural strength was recommended as the standard mix design and standard sampling method for the District. The results of the tests show that the control mix sampled using the standard Proctor Hammer method of compaction resulted in the highest compressive strength of 3,500 pounds per square inch (psi) with a corresponding coefficient of permeability of 57.82 inches per hour (in/hr) and modulus of rupture of 565 psi.

The summary table presented in this section is the recommended mix that was developed by Superior Concrete Materials, Inc. for the green alley paving and used in several pilot projects in Ward 7 of the District of Columbia. The trial mixes used in this study were compared to this mix. In-situ infiltration tests conducted on at 3 of the pilot locations with the optimal pervious concrete mix yielded average infiltration rates between 86.1 and 208.7 in/hr, which are within the average pervious concrete infiltration rates (i.e., 100 to 200 in/hr).

Content	Quantities/Specifications
Cement, Holcim	29.6 lb
Fly Ash	8.5 lb
#8 Stone (Millville)	208.8 lb
Sand (Howlin)	5.6 lb
Water	13 lb
HRWR	0.22 lb
Hydromax (Internal curing Ad-mixture)	0.11 lb
Delvo (Hydration Stabilizer)	4.6 -10.7 oz
W/C (Water Cement Ratio)	0.34
Cement percent of total weight	15.11
Sand percent of total weight	2.20
Gravel percent of total weight	82.69

1.0 INTRODUCTION

Pervious concrete is a mixture of Portland cement, aggregate, and water that provide a level of porosity which allows water to percolate into the sub-grade. It differs from the conventional concrete since it usually contains a nominal amount of fine aggregate. Pervious concrete is comprised of single size aggregates which result in larger air voids than conventional concrete.

Impervious roadways contribute to higher runoff, which overburdens stormwater conveyance systems. A 10-year, 6-hour duration event could produce 3.31 inches of precipitation in the District, according to the National Oceanic and Atmospheric Administration. The District of Columbia has a land area of 61.05 square miles, so with 43% of the District being impervious, the aging storm conveyance system could be subjected to 58.8 million cubic foot of stormwater if there is a 3.31 inch rain event. Stormwater can collect numerous materials that are toxic to animals, the environment, and all water sources.

Most major cities have stormwater conveyance systems that were built in the early 1900s, which provide a conventional capture of the stormwater runoff. With urbanization and population growth, a substantial number of stormwater systems are becoming increasingly inefficient in managing runoff. In recent years, low impact technologies are increasingly being applied to developments where runoff is treated on site. Onsite treatment systems include ponds, infiltration basin, porous concrete, porous asphalt, swales, and filter strips. Depending on the hydraulic characteristics of the underlying soil strata, water that goes through a pavement base slowly recharges the ground water or is collected through under drains and discharged to stormwater lines.

Pervious concrete, also known as porous concrete (enhanced porosity) or gap-graded concrete has little to no fine aggregates. Pervious concrete mixes consist of cement, single sized coarse aggregate and water (water/cement ratio ranging 0.3 to 0.4). It is reported that, the 28-day compressive strength of such mixes range from 800 psi to 3,000 psi based on compressive strength testing per ASTM C39. In addition, pervious concrete mixes vary among batch manufacturers with varying strengths and permeability rate. Since the mid-1970's, interest in the use of pervious concrete has grown throughout the United States. The benefits from its use are its potential to:

- Reduce the quantity of runoff water
- Improve water quality
- Enhance pavement skid resistance, especially during storm events by rapidly draining rain water
- Reduce traffic-induced noise levels

Several agencies, including the National Concrete Pavement Technology Center at Iowa State University, U.S. Environmental Protection Agency (EPA), Boston Metropolitan Area Planning Council, California Stormwater Quality Association, Colorado Ready Mix Concrete Association, and Middle Tennessee State University have conducted research and/ or compiled research studies on pervious concrete pavements in their local jurisdictions. The studies conducted at Iowa State University Technology Center found that in cold climatic regions with hard wet-freeze environments, the use of pervious concrete is limited.

Under the Clean Water Act, the EPA has identified pervious concrete as an alternative to meet stormwater regulation requirements. Since 43% of Washington D.C.'s land area is deemed to be impervious, meeting the federal requirement is a challenge. The District Department of Transportation (DDOT) embarked on its first green alley construction project with the assistance of the staff of National Ready Mix Concrete Association (NRMCA) who trained and certified DDOT technicians on the inspection and placement of pervious concrete. DDOT did not have the knowledge of the tools or procedures needed to perform quality control inspection of the pervious concrete. NRMCA provided a permeable concrete design mix which was used as the basis (control mix) for this study. This research conducted a series of field concrete tests, laboratory compressive strength and permeability tests on several pervious concrete mix designs in order to identify the optimum mix. Standard guidelines for quality assurance and quality control were also established. The findings of this research could be used by DDOT in establishing acceptable field test guidelines for pervious concrete in alleys and elsewhere.

2.0 RESEARCH OBJECTIVES

The use of pervious concrete to date has been limited to low volume and low speed traffic areas such as parking lots and sidewalks. These facilities are not typically subjected to high volume and standard wheel loads. Many jurisdictions are now considering the use of pervious concrete on low volume roads such as residential streets and alleys. DDOT is now testing pervious concrete in its “green alleys” program. Fully loaded trash trucks, over time, can cause the premature failure of pervious concrete pavement. Thus, pervious concrete pavement mix must be designed to withstand the anticipated level of loading from heavy vehicles. The design mix and physical characteristics of pervious concrete to be used in the District need to be investigated. As a result, the objectives of this research are:

- Develop and test five pervious concrete design mixes (including the control mix)
- Recommend the optimal mix based on the results of the analysis.
- Establish guidelines for sampling and testing pervious concrete mixes in the laboratory and the field.

3.0 LITERATURE REVIEW

The environmental benefits of pervious concrete include the removal of pollutants from surface run-off and replenishment of ground water sources. Tennis, Lemming, and Akers stated that pervious concrete traps fluids such as oil and anti-freeze from automobiles, inhibiting them from flowing into nearby water sources during rainstorms. Although pervious concrete is not usually used for roadways that convey high traffic volume, its surface can improve safety during rainstorms by eliminating ponding, spraying, and risk of hydroplaning. Pervious concrete could have compressive and tensile strengths ranging from 500 to 4,000 psi and 150 to 550 psi, respectively (Tennis et al., 2004). Whereas traditional concrete has compressive strength and tensile strength ranging from 3,500 to 5,000 psi and 350 to 600 psi, respectively. However, it is possible to attain a stronger pervious concrete with the addition of admixtures and fiber (Amde et al., 2013).

In February 2013, the State of Maryland examined various mixes to develop high quality pervious concrete for the State's specification. The research was conducted using material from recent projects in the State of Maryland with the primary focus on specific admixtures that could be used to enhance the performance of pervious concrete. The admixtures used were cellulose fiber, a delayed set modifier, and a viscosity modifier. Samples of the pervious concrete were tested for density, void content, compressive strength, split tensile strength, permeability, freeze-thaw durability, and abrasion resistance. Fully saturated, 50% saturated, 0% saturated, and dry hard-freeze tests were investigated for freeze-thaw durability. The mixes with cellulose fiber resulted in significant increases in resistance to freeze-thaw activities. The cellulose fiber in the mixture bonded the cement and course aggregates thereby improving the tensile strength of the pervious concrete. In addition, the delay set modifier admixture was determined to increase the compressive strength which was attributed to lower water cement ratio. Finally, the viscosity modifying admixture created a more workable and easier to mold mix. Its effect on strength and durability, however, was determined to be minimal (Amde et al., 2013).

In 2007, a study conducted in Florida investigated the compressive strength and permeable characteristics of pervious concrete. The study revealed that the strength of pervious concrete not only relies on the compressive strength, but the soil strata below it. In addition, the researchers compared the compressive strength of conventional concrete and pervious concrete. The results of the analyses showed that pervious concrete has lower compressive strength than conventional concrete. The researchers concluded that pervious concrete can only support light traffic loadings. The authors determined that the following factors affect the strength and permeability of pervious concrete: compaction, aggregate size, water cement-ratio, and aggregate cement ratio. The tests were conducted in a laboratory with varied concrete mixtures and cylinders. The outcome of the experiment validated the fact that permeable concrete has lower compressive strength than conventional concrete (Chopra et al., 2007).

A review article in 2007 summarized a number of studies on permeable concrete. The authors indicted that the life span of pervious pavement depends on the size of air voids in the pavement. The synthesis contends that the life span of pervious concrete is usually shorter than the typical concrete pavement. However, in most cases, after many years of usage, the pervious pavements were determined to be more effective in containing and infiltrating the runoff. Consequently, the pavement reduced zinc and copper levels while infiltrating the runoff. While impervious surfaces have a high potential for increasing pollution in water bodies, porous or permeable pavements are generally noted to reduce pollutants. Permeable pavements that do not have underlying filtration systems are generally not successful in removing pollutants. The study also reports that the long-term cost of permeable pavements with regards to its maintenance and operations are yet to be determined (Scholz et al., 2007).

An experiment was recently conducted to determine the potential application of fly ash in pervious concrete. Natural sand and fiber was also included in the mix to test the potential for enhancing the strength of the pervious concrete. The study investigated six batches of pervious concrete with varying aggregates, cement, and fly ash. Each mix was analyzed, and the mix with the high compressive strength and high permeability was chosen. The mix proportions were taken from mix designs used in earlier studies. Compressive tests were carried out on mixtures with the following fly ash content: 0%, 2%, 9%, 30%, and 32% by weight of total cement material. For mixtures with 2% and 32% fly ash, a falling head permeability test was conducted. The use of fly ash was determined to significantly increase the strength and durability of the pervious concrete. The study concluded that it was possible to achieve a concrete which was permeable and whose strength meets the pavement design specifications. The study concluded that for the mixture with 2% fly ash, the achieved compressive strength was 2,300 psi with a permeability rate of 184.25 in/hr and 15% voids. In contrast, the pervious concrete mix with 32% fly ash had a compressive strength of 2,000 psi and a permeability rate of 297.64 in/hr at void content of 15.8%. Further analysis of the mix with 2% fly ash indicated a higher strength of cement bonding. The failure of the specimen containing 32% fly ash indicated that admixtures resulted in a weaker cement bonding (Jin, 2013).

A long term study of stormwater quantity and performance of permeable pavement systems provided the opportunity for evaluating the long term effectiveness of the permeable pavement. Impervious surfaces have long been implicated in the decline of watershed integrity in urbanized areas. Most of these impervious areas serve as a vehicle for pollutant to migrate into ecosystems and streams. Research conducted in Reston, Virginia observed the behavior of permeable pavement over six year duration. Four pairs of different permeable pavements were constructed in that study. Soil properties were studied prior to picking the site. The pavements were 9.8 ft wide by 19.7 ft long. Mechanisms were installed to collect both subsurface and surface runoff. After precipitation events, water samples were collected and analyzed. The permeable pavements studied had differing results, but the general trend in reduction of stormwater pollutant was observed for the most porous specimens that met the minimum requirement. Runoff performance was very good; all pavements infiltrated virtually all precipitation (Booth et al., 2003).

A study conducted by Iowa State University in 2008 summarized the results of improved freeze-thaw durability of pervious concrete. The pervious concrete mix was developed using Portland cement, sand, and polypropylene fibers. The engineering properties of the aggregate, porosity, permeability, strength, and freeze-thaw durability of pervious concrete mixtures were analyzed. The experiment was conducted using 14 different mixtures according to the ASTM Standard C666-97. Statistical Analyses were conducted to identify the statistical significance of observed differences. The result revealed that using sand increased strength while decreasing permeability and using fiber increased the optimal porosity of the concrete more than the mix without the fiber (Kevern et al., 2008).

A study conducted by Kevern et al. used the self-consolidating method to prepare the pervious concrete. That method uses gyration to consolidate the mix uniformly and improve the porosity and strength of the concrete. The best design mix contained crushed graded course aggregate, 10% fine aggregate, binder of 24% by mass, and water cement ratio of 0.29. All combinations of chemical admixtures improved the initial workability. However they decreased the required compaction energy needed. The experiment is still ongoing and proposes to determine the optimal strength and porosity of pervious concrete mix design (Kevern et al., 2008).

A study conducted in Knoxville, TN in 2009 investigated soil condition below the concrete pavement that could increase the infiltration rate of pervious pavements. Four types of soil conditions were studied: no treatment of soil, trenched-soil trenched, ripped- subsoil, and boreholes. The research used 23 by 49 feet rectangular field site with predominately clay sub soil. Infiltration data was collected over a period of two years. The results showed an improvement in the infiltration rate of the pervious pavements on a treated sub grade compared to the control group without treatment (Tyner el al., 2009)

A report prepared by James et.al recommended the use of pervious concrete as a solution for managing stormwater runoff. They recommended that pervious concrete should have air void content 15% to 30%; 100 to 120 lbs/ft^3 for unit weight; and 2,500 to 3,500 psi for strength. The report recommended an infiltration rate: 0.1–0.5 in/hr. The researchers also discussed the potential environmental disasters and the advantages of using pervious concrete. Placement and best practices in installing pervious concrete were presented. The report covered the inspection and maintenance aspect of pervious concrete pavements, freezing, clogging, the life span and maintenance (James, 2010).

In summary, the literature shows that the testing of various pervious concrete batches with admixtures to achieve an ideal design mix is actively ongoing. Researchers continue to adjust design mixes to improve void ratios, infiltration rates, porosity, and strength of the concrete. These studies may potentially result in the adaption of mixtures that are suitable to the needs in the region for which they will be applied. The ideal mix design will be based on the jurisdictions needs to accommodate weather, traffic volumes and environmental impacts of stormwater runoff. Current permeable field tests are limited to alleys and parking lots. The outcome of tests on design mixes, maintenance methodologies, and lifecycle of the mix designs will require an extended period of time. Typical infiltration rates of pervious concrete have been documented in several field tests which vary based on the underlying soil characteristics and/or jurisdiction. Several studies indicate that pervious concrete allows water to infiltrate at very high rates, typically from 100 to 200 in/hr.

4.0 RESEARCH METHODOLOGY AND DATA COLLECTION

The first part of this study focused on testing pervious concrete mix designs to see which would yield the optimal compressive strength, flexural strength, and permeability. Four design mixes were tested and compared with a control mix. The control mix design was developed by Superior Concrete, a concrete plant in Washington DC. The mix had been used in pervious concrete paving of six green alley projects in Ward 7, located in northeastern section of Washington, DC. Materials and chemical additives for this study were provided by Superior Concrete. Pervious concrete mixing, sampling, and testing were conducted at the DDOT Materials Testing and Research Laboratory. The four design mixes were achieved by varying the sand content and introducing fiber to potentially improve the compressive and flexural strength of pervious concrete. The consolidations of the specimens were conducted in 3 different ways: self-consolidating, rodded, and Proctor Hammer. The Maryland Ready Mix Concrete Association trained and certified the research team in the placement and quality control of pervious concrete. The pertinent variables and data collection scheme for this research were developed from information observed in the literature review and industrial standards. Based on the literature review, the following methodologies were employed.

4.1 Mix Design

Although pervious concrete contains the same basic ingredients as the conventional concrete, the proportions of the ingredients can vary. One major difference is the requirement of increased void content within the pervious concrete. The amount of void space is directly correlated to the permeability of the pavement. The need for void space within the mix design correlates with using little to no fine aggregates. The porous concrete mix designs adopted for this study were based on materials that were readily available in the metropolitan area. The mix consisted of 200 lbs of #8 Stone (Millville), little to no fine aggregates, cement type I-/II, and macro/micro fibers. The mix also included admixtures including a Viscosity Modifying Admixture (VMA), an air entraining agent, and a High-Range Water Reducer (HRWR). These admixtures are used to potentially improve the bond between the cement and the coarse aggregate, and to improve workability as well as flexural properties of the pervious concrete. A retarder was also included since the low water content of porous concrete pavement mixes causes them to dry quickly. The sand content was varied for all mixes. Trial batches were prepared and tested for acceptable unit weights and percent voids. The mix proportions for the pervious concrete samples are summarized in Table 1.

4.2 Sample Preparation Procedure

As in conventional concrete, the pervious concrete samples were mixed using a mechanical mixer. The constituent weights were prepared and batched. The mechanical mixer was initially buttered with a sample batch to avoid loss of material. Thereafter, the mixer was stopped and cleaned to remove excess water and material. The coarse aggregates and half the measured water were then added to the mixer. After which sand and cement materials were slowly added into the rotating drum mixer. The remaining half of the water was then added, while mixing continued for three minutes from start time. The mixer was stopped for three minutes, and finally run for an additional two minutes. Unit weights and temperature of the fresh concrete were determined per ASTM C1685. Accordingly, pervious concrete samples of 4 in. x 8 in., and beams 6 in. x 6 in. x 21 in. beams were prepared.

The cylinder and beam samples were made and cured in accordance with ASTM C192 *Standard Practice for Making and Curing Concrete Test Specimen in the Laboratory*. The samples were cast using the following methods:

- Self-Consolidating (SC): also referred to as self-compacting. The cylinder was completely filled and struck and capped under pressure.
- Standard Rodding (SR): samples were prepared in two lifts and compacted 25 times with a tamping rod. The samples were also tapped on the sides slightly after the first and last rodding.
- Proctor Hammer (PH): samples were placed into cylinders in two lifts and compacted with 25 times of the standard Proctor Hammer.

The specimens were cured in a standard moisture curing chamber, until the day of testing. A minimum of 4 samples were prepared for each mix, of which two were used for compressive strength tests while the remaining were used for permeability and percent void analysis.

Table 1. Pervious Concrete Mix Design

Mix Design	Control Mix	Mix 1	Mix 2	Mix 3	Mix 4
Cement, Holcim	29.64 Ib	29.64 Ib	29.64 Ib	29.64 lb	29.64 lb
Fly Ash	8.52 Ib	8.52 Ib	8.52 Ib	8.52 lb	8.52 lb
#8 Stone (Millville)	208.8 Ib	206.9 Ib	205.1 Ib	203.2 lb	201.4 lb
Sand (Howlin)	5.56 Ib	7.41 Ib	5.56 Ib	11.12 lb	12.97 lb
Water	13 Ib	13 Ib	13 Ib	13 Ib	13 Ib
HRWR	0.22 Ib	-	-	-	-
Hydromax (Internal curing Ad-mixture)	0.11 Ib	-	-	-	-
Delvo (Hydration Stabilizer)	4.58 - 10.68 oz	2 - 4oz	2 – 4 oz	2 – 4 oz	2 – 4 oz
Fibers (Micro)	-	-	134.4 g	134.4 g	-
W/C (Water Cement Ratio)	0.34	0.34	0.34	0.34	0.34
Cement percent of total wt.	15.11	-	15.11	15.11	15.11
Sand percent of total wt.	2.20	2.93	2.20	4.40	5.13
Gravel percent of total wt.	82.69	81.96	81.22	80.49	79.76

4.3 Compressive Strength

Seven-day and 28-day compressive strength tests were performed in accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. The pervious concrete samples were capped with neoprene pads before being placed in the loading frame for testing as shown in Figure 1. An example of a failed sample is presented in Figure 2. A total of six samples were used for the strength test, with two specimens made for each different compaction technique described earlier (SC, SR and PH). The height and diameter were measured and recorded. Table 2 shows the temperature and unit weights of the five samples.

Figure 1. Concrete cylinder placed in a loading frame

Figure 2. A Sample of Failed Pervious Concrete

Table 2. Unit Weights and Temperatures of New Pervious Concrete

	Control Mix	Mix 1	Mix 2	Mix 3	Mix 4
Temperature (^{0}F)	72	70	68	80	85
Unit weight (lb)	125.6	126.8	118.0	120.4	119.8

4.4 Flexural Strength

After the 28-day curing period, the prepared pervious concrete beams (plain and fiber-reinforced) were tested for flexural strength properties. The tests were conducted in accordance with the third point loading of ASTM C293. The modulus of rupture was computed for use in thickness design of pervious concrete structures. The sample breaks were in the middle third of the span. The modulus of rupture (M_R), was computed using the following formula:

$$M_R = (P*L)/(B*D^2)$$

where *P*= the load (force) at the fracture point
L = Span length (distance between supports)
B = width
D = thickness

4.5 Porosity, Air Voids and Density Tests

The unit weight, maximum specific gravity, and bulk specific gravity for each sample were determined using a Corelok automatic vacuum and sealing apparatus shown in Figure 3.

Figure 3. Corelok

The unit weight of freshly mixed concrete was measured on all mixes immediately after the mechanical mixing was completed. Pervious concrete has high interconnected air voids, thus it is not suitable to use the submerged weight measurement to obtain the bulk volume. As a result, the vacuum package sealing device, Corelok, was used to obtain the effective air voids (e) and porosity (n) of the pervious concrete specimens. Figure 4 is a sample of sealed pervious concrete that has been placed in the Corelok.

The void ratio and porosity were calculated using the following formulas:

$$e=\frac{V_v}{V_s}$$

where e= void ratio, V_v=Volume of Voids, and V_s=Volume of Voids

$$n=\frac{V_v}{V_t}$$

where n=porosity, V_v=volume of voids and V_t=total volume

Figure 4. A Sealed Pervious Concrete Sample Placed in Corelok

4.6 Permeability Test

Permeability refers to the ease with which water can flow through pervious concrete. The permeability of each sample, *K*, was computed using the following formula:

$$K=(Q*L)/(A*t*h),$$

where Q = Volume
L = Length
A = Area
t = time
h = head

Each sample was subjected to a 1 inch head over the saturated sample for a period of 60 seconds after which the water level was measured and recorded. The average diameter was measured and calculated for each sample.

5.0 RESULTS

5.1 Compressive Strength Tests

The compressive strength test was performed on all five mix designs. Two samples were tested for each mix the average of the compressive strength was determined. Specimen with two curing times (7-days and 28-days) was used in the compressive strengths test. The diameter of each sample was measured at the top, and bottom after which the average was used to calculate the cross-sectional area. The compressive strength was then calculated by dividing the average final maximum load recorded by the average cross-sectional area of the cylindrical specimen. Table 3 presents the results of the 7-day and 28-day compressive strengths for each mix design.

Table 3. Compressive Strength (psi)

	Self-Consolidating		Rodded		Proctor Hammer	
Mixes	**7 days**	**28 days**	**7 days**	**28 days**	**7 days**	**28 days**
Control	1,350	2,510	3,330	1,290	2,615	3,575
1	725	2,190	3,035	1,210	2,170	2,675
2	623	1,165	1,260	690	1,745	1,900
3	390	1,320	1,710	620	1,445	1,665
4	570	1,050	1,055	675	1,845	1,960

Each specimen was loaded until the load began to decrease rapidly. The fracture types were recorded and are presented in the Appendix.

From the table, the compressive strengths of the pervious concrete using the self-consolidating method were found to be the least for all the mix designs for both the 7-day and 28-day curing times while the

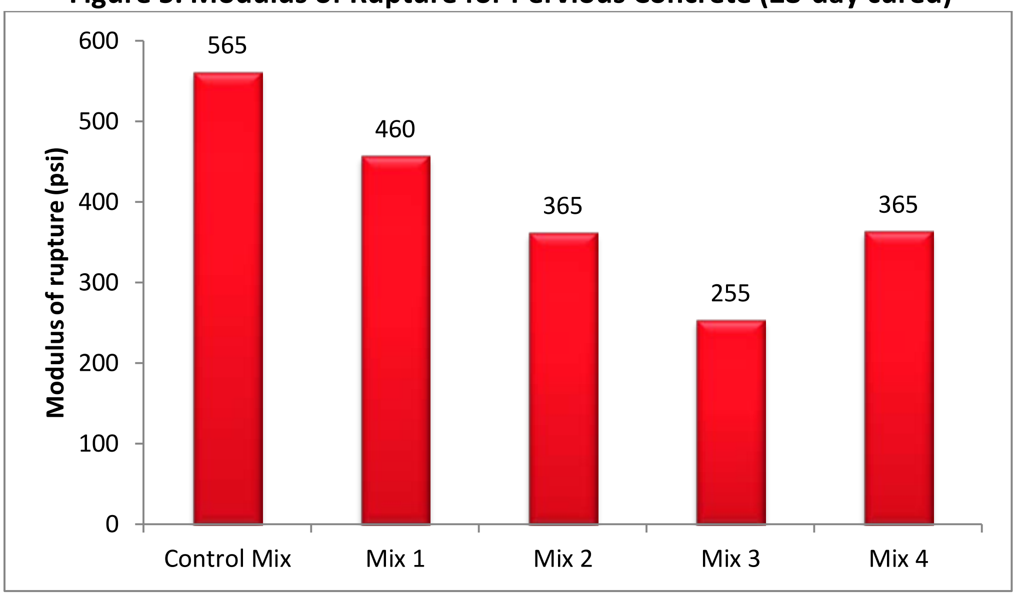
Proctor Hammer method yielded the highest compressive strengths for both curing times. The 7-day compressive strengths for the mixes were generally lower than their corresponding 28-day compressive strengths. The compressive strengths varied from 370 psi to 3,575 psi for the 7- and 28-day curing times. The results of the analysis also show that the control mix had the highest average compressive strength for both the curing times.

The mixes which had the fibers (Mix 2 and Mix 3) did not show an increased compressive strength over the control mix. Generally, on average, the compressive strength was highest for the control mix, followed by Mix 1, with the remaining mixes showing marginal differences.

5.2 Modulus of Rupture

The modulus of rupture is defined as a material's ability to resist deformation under load. The results of the test conducted to determine the ability of the pervious concrete beams to resist deformation (with failure occurring in the middle third of the span) are presented in Figure 5. This was conducted only for the samples which were cured after 28-days. The control mix had the highest modulus of rupture (565 psi) and therefore the highest resistance to deformation under load.

Figure 5. Modulus of Rupture for Pervious Concrete (28-day cured)



5.3 Voids

Table 4 presents the results of the percent voids in the pervious concrete mixes for the self-consolidating, rodded, and Proctor Hammer compaction methods respectively. The void space between the aggregates provides the opportunity for water to flow through the concrete. The results show that the pervious concrete mixes had a higher percent voids under the self-consolidation compaction method that under the remaining two compaction methods. The average voids was approximately 19% for the self-consolidation method while the rodded and Proctor Hammer compaction method were both approximately 18%.

Table 4. Voids (%)

Mixes	Self-Consolidating	Rodded	Proctor Hammer
Control	25	13	16
1	19	20	17
2	19	20	15
3	16	16	23
4	17	21	17
Average	**19**	**18**	**18**

5.4 Porosity

The results of the porosity tests are presented in Table 5, for the self-consolidation, rodded and Proctor Hammer compaction methods respectively. As shown in the tables, the self-consolidated mixes had the higher porosity, compared with their corresponding mixes under rodded and Proctor Hammer compaction methods. The highest porosity of 20% was achieved in Control Mix (Self-Consolidating) while the lowest porosity of 11% was obtained in the Control Mix (Standard Proctor Hammer).

Table 5. Percent Porosity and Bulk Specific Gravity

	Self-Consolidating		Rodded		Proctor Hammer	
Mixes	**Bulk Specific Gravity**	**Porosity (%)**	**Bulk Specific Gravity**	**Porosity (%)**	**Bulk Specific Gravity**	**Porosity (%)**
Control	1.89	20	2.06	11	2.07	14
1	1.86	19	2.04	17	2.11	14
2	1.74	19	1.88	16	1.89	13
3	1.79	16	1.93	14	1.98	18
4	1.85	17	1.87	17	2.07	15

5.5 Coefficient of Permeability

The results of the permeability tests conducted on the design mixes for each compaction method is presented in Table 6. The results show the average permeability rates for the permeability tests run twice for each mix.

Table 6. Summary of Permeability Tests

Mix	Average *K* (in/hr)		
	Self-Consolidated	Rodded	Proctor Hammer
Control	299.5	82	57.82
1	302.4	106.7	71.1
2	299.6	202.5	90.7
3	209.7	83.4	107.9
4	291.4	224.9	136.5

6.0 DISCUSSION

The results of the analysis indicate that the method of compaction influenced the compressive strength of the pervious concrete. As shown in the tables and plots, the strength increased using the self-consolidating method, half- rodded method, and the standard Proctor Hammer. The standard Proctor Hammer method provided the highest compressive strength (3,575 psi) for the samples cured over a 28-day period. This was attained for the Control Mix. Contrary to expectations, that the mix designs which contained fiber (Mix 2 and Mix 3) did not show a higher strength compared to the Control Mix. This could be potentially due to the lack of cement and aggregate bonding thereby reducing their ability to sustain the maximum loading. Mixes 1, 3, and 4 also had a higher sand content than the Control Mix (and Mix 2) which could have been a factor in the reduced compressive strengths in those mix designs. The Control Mix's highest compressive strength could also be attributed to the presence of the HRWR and Hydromax (which is an internal curing add-mixture) while the other four mix designs did not. Finally, the hydration stabilizer, Delvo, used in a higher quantity than the 4 mixes, could have also played a role in the higher compressive strength in the Control Mix since it is thought to enhance workability and provide improved compressive strength

The flexural strengths (modulus of rupture) of the 28-day cured pervious concrete ranged from 250 psi to 550 psi with the Control Mix showing the highest strength of 550 psi. The decline in flexural strengths from the Control Mix through Mix 4 could be attributed to the reduced #8 stone content of the mixes with the Control Mix having the highest #8 stone content of approximately 209 lbs. Delvo, which was used a higher quantity in the control mix, adsorbs on the surface of cement materials, forms a protective barrier and controls the setting characteristics of concrete and acts as a dispersant, providing water reduction, thereby potentially increasing the flexural strength of the Control Mix over the other mixes.

The results of the analysis show that the porosity of the pervious concrete decreased with increasing effort of compaction. The self-consolidation has the least effort of compaction while the standard Proctor Hammer has the highest. As a result, all the five design mixes showed a decline in porosity with increasing compaction effort. The highest porosity (~36%) was attained in Mix 3 under self-consolidation while the least was in the Control Mix (~17%) under the standard Proctor Hammer compaction method.

The self-consolidated samples provide higher infiltration rates and thus are more pervious. However, from the analysis they have the least compressive strengths.

The literature suggests that the porosity of a concrete sample correlates to its hydraulic conductivity. The hydraulic conductivity is usually measured in terms of the coefficient of permeability. From the results, the coefficients of permeability of the samples were influenced by the compaction method used to prepare the samples. The coefficient of permeability ranged from 209.7 to 302.4 in/hr for the self-conducted samples, 82 to 224.9 in/hr for the rodded samples and 57.8 to 136.5 in/hr for the standard Proctor Hammer compaction method.

7.0 FIELD INFILTRATION RATE TEST PROCEDURES

The field infiltration test is conducted in accordance with the procedures of ASTM C1701, which is the standard test procedure for determining the infiltration rate of a pervious concrete. The test involves first cleaning the pervious concrete pavement after which a 12.25 inch diameter infiltration ring is installed (see Figure 6). The ring is secured in place with plumber's putty after which the concrete is pre-wet with 8 pounds of water. The head of water between the two marks on the interior of the ring should be maintained throughout the test. A time clock is started as soon as the water is poured on to the pervious concrete until there is no water in the ring. This elapsed time provides an indication of the quantity of water to be used in the actual test. Typically, about 40 pounds of water is used for this test.

Figure 6. Single-ring Infiltrometer (ASTM C1701)

At least 2 minutes after the pre-wetting phase, the same procedure is repeated, again, maintaining the water head between the two rings. The weight of the actual water used in this phase is then measured. The time elapsed when no water is present in the ring is also measured again. With the data obtained (weight of water, time elapsed, diameter of ring), the infiltration rate can be computed using the following formula:

$$K = (kM)/(D^2 * t)$$

where k is the constant 126,870, M is the weight of water, D is the diameter of ring, and t is the time elapse when testing. The unit of the infiltration rate is in in/hr.

7.1 In-Situ Unit Weight Tests

From the literature, pervious concrete is not solely accepted or specified based on strength, but more importantly to the success of a pervious pavement with an acceptable void content. The acceptance is typically based on the density (unit weight) of the in-situ pervious pavement. Based on several studies, including field tests conducted by DDOT on pervious concrete constructed at 3 locations, an acceptable tolerance is plus or minus 5 lb/ft^3 (80 kgm^3) of the design density. This should be verified through field testing. The fresh density (unit weight) of pervious concrete should be measured using the jigging method described in ASTM C 29.

7.2 In-Situ Infiltration Tests

The field infiltration test was conducted using the standard infiltration ring with inside diameter of 12.25 inches. Based on a *K* value of 126,870 inches, the amount of water that infiltrates the pervious concrete pavement over a time period (usually up to 10 minutes) was measured (based on the difference in the level of water remaining in the infiltration ring). From the values obtained, the infiltration rate (in/hr) can be calculated. A minimum of 2 locations per pervious concrete section should be tested.

The infiltration rates of the pervious concrete installed at 3 locations in DC were obtained in the field using the procedures mentioned. The detailed results are presented in the Appendix. From the tests, the average infiltration rate for the 3 sites ranged between 86.1 and 208.7 in/hr which falls within the typical infiltration rate range of pervious concrete (i.e., 100 to 200 in/hr).

7.3 Cleaning of Pervious Concrete

It is recommended by the Environmental Protection Agency that, to prevent clogging, pervious concrete pavement must be cleaned regularly, through vacuum sweeping or high pressure washing.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The ideal pervious concrete mix is expected to provide the maximum compressive strength, and the optimal infiltration rate. Especially for pervious concrete used on roadways, there is the need for it to be able to withstand various traffic loadings while providing adequate infiltration to reduce surface runoffs. From the results of the analysis, the Control Mix is recommended which showed a maximum compressive strength of 3,500 psi with a coefficient of permeability ranging between 57.8 and 299.5 in/hr. The standard Proctor Hammer compaction method should be used in preparing the pervious concrete for use in the field. The average infiltration rate of the field tests conducted on the pervious concrete was determined to be between 86.1 and 208.7 in/hr, which falls within the typical infiltration rate range of pervious concrete (i.e., 100 to 200 in/hr).

Based on the outcome of this research, the following recommendations are made:

- Consider the deployment of pervious concrete on local/residential streets and conduct field tests to monitor their performance of deployed pervious concrete over time.

- Incorporate the Control Mix design into materials specifications for DDOT together with the field test procedures using ASTM C1701 outlined in Section 7.

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APPENDICES –
DATA COLLECTION AND ANALYSIS

A-1: STRENGTH TEST RESULTS

Mix Type	Lab #	Test Date	D1 (in)	D2 (in)	Failure Load (lb)	Break Type	Age (days)	Load (psi)	Average (psi)
Control Mix									
Self-Consolidate	987	5/14/2013	4	4	17,170	Cone/Shear	7	1,366.4	**1,347.6**
	987	5/14/2013	4	4	16,700	Shear	7	1,328.9	
	987	6/4/2013	4	4	18,420	Shear	28	1,465.8	**1,286.8**
	987	6/4/2013	4	4	13,920	Cone/Split	28	1,107.7	
Rodded	989	5/14/2013	4	4	31,870	Cone/Split	7	2,536.1	**2,505.9**
	989	5/14/2013	4	4	31,110	Shear		2,475.7	
	989	6/4/2013	4	4	40,660	Cone/Split	28	3,235.6	**3,325.9**
	989	6/4/2013	4	4	42,930	Cone/Split		3,416.3	
Proctor Hammer	988	5/14/2013	4	4	28,950	Shear	7	2,303.8	**2,611.3**
	988	5/14/2013	4	4	36,680	Cone	7	2,918.9	
	988	6/4/2013	4	4	45,720	Cone/Split	28	3,638.3	**3,574.6**
	988	6/4/2013	4	4	44,120	Cone/Split	28	3,511.0	
Mix 1									
Self-Consolidate	992	5/14/2013	4	4	7,440	Cone/Split	7	592.0	**724.6**
	992	5/14/2013	4	4	10,770	Cone/Split	7	857.0	
	992	6/4/2013	4	4	15,600	Shear	28	1,241.4	**1,206.8**
	992	6/4/2013	4	4	14,730	Shear	28	1,172.2	
Rodded	990	5/14/2013	4	4	23,920	Shear	7	1,903.0	**2,187.6**
	990	5/14/2013	4	4	31,060	Cone/Shear	7	2,472.0	
	990	6/4/2013	4	4	40,090	Cone	28	3,190.3	**3,032.7**
	990	6/4/2013	4	4	36,130	Shear	28	2,875.1	
Proctor Hammer	991	5/14/2013	4	4	26,920	Cone	7	2,096.0	**2,168.5**
	991	5/14/2013	4	4	28,160	Cone	7	2,241.0	
	991	6/4/2013	4	4	33,660	Shear	28	2,678.6	**2,674.6**
	991	6/4/2013	4	4	33,560	Cone	28	2,670.6	

Mix Type	Lab #	Test Date	D1 (in)	D2 (in)	Failure Load (lb)	Break Type	Age	Load (psi)	Average (psi)
Mix 2									
Self-Consolidate	1020	5/22/2013	4	4	5,920	Shear	7	471.1	**622.0**
	1020	5/22/2013	4	4	9,730	Shear	7	774.3	
	1020	6/12/2013	4	4	9,040	Shear	28	719.4	**687.0**
	1020	6/12/2013	4	4	8,250	Shear	28	656.5	
Rodded	1021	5/22/2013	4	4	14,520	Shear	7	1,155.5	**1,162.6**
	1021	5/22/2013	4	4	14,700	Shear	7	1,169.8	
	1021	6/12/2013	4	4	15,320	Cone/Shear	28	1,219.1	**1,259.7**
	1021	6/12/2013	4	4	16,340	Shear	28	1,300.3	
Proctor Hammer	1022	5/22/2013	4	4	20,020	Shear	7	1,891.6	**1,742.3**
	1022	5/22/2013	4	4	23,770	Shear	7	1,593.1	
	1022	6/12/2013	4	4	23,050	Shear	28	1,834.3	**1,896.7**
	1022	6/12/2013	4	4	24,620	Shear	28	1,959.2	
Mix 3									
Self-Consolidate	1023	5/22/2013	4	4	6,750	Shear	7	537.00	**388.3**
	1023	5/22/2013	4	4	3,010	Shear	7	239.50	
	1023	6/12/2013	4	4	7,950	Shear	28	632.60	**619.1**
	1023	6/12/2013	4	4	7,610	Shear	28	605.60	
Rodded	1024	5/22/2013	4	4	17,400	Shear	7	1,384.60	**1,318.6**
	1024	5/22/2013	4	4	15,740	Shear	7	1,252.50	
	1024	6/12/2013	4	4	22,510	Shear	28	1,791.30	**1,706.5**
	1024	6/12/2013	4	4	20,380	Shear	28	1,621.80	
Proctor Hammer	1025	5/22/2013	4	4	17,770	Shear	7	1,414.10	**1,445.1**
	1025	5/22/2013	4	4	18,550	Cone/Split	7	1,476.20	
	1025	6/12/2013	4	4	20,670	Shear	28	1,644.90	**1,663.2**
	1025	6/12/2013	4	4	21,130	Shear	28	1,681.50	

Mix Type	Lab #	Test Date	D1 (in)	D2 (in)	Failure Load (lb)	Break Type	Age	Load (psi)	Average (psi)
Mix 4									
Self-Consolidate	1026	5/22/2013	4	4	6,540	Shear	7	520.4	**568.6**
	1026	5/22/2013	4	4	7,750	Shear	7	616.7	
	1026	6/12/2013	4	4	8,610	Shear	28	685.2	**670.4**
	1026	6/12/2013	4	4	8,240	Shear	28	655.7	
Rodded	1027	5/22/2013	4	4	11,840	Shear	7	942.2	**1,048.0**
	1027	5/22/2013	4	4	14,500	Cone/Split	7	1,153.9	
	1027	6/12/2013	4	4	13,050	Shear	28	1,038.5	**1,052.0**
	1027	6/12/2013	4	4	13,390	Shear	28	1,065.5	
Proctor Hammer	1028	5/22/2013	4	4	24,430	Shear	7	1,944.1	**1,843.8**
	1028	5/22/2013	4	4	21,910	Cone/Split	7	1,743.5	
	1028	6/12/2013	4	4	24,940	Cone/Split	28	1,984.7	**1,959.6**
	1028	6/12/2013	4	4	24,310	Cone/Split	28	1,934.5	

**D1 and D2: diameter of the cylinder*

A-2: MODULUS OF RUPTURE

Mix Type	Lab. No.	Test Date	Depth (in)	Width (in)	Span Length (in)	Failure Load (lbs)	Break Type	Age days	Modulus of rupture (psi)
Control Mix	987	6/14/2013	6	6	18	6,732	Middle 3rd	28	**561.0**
Mix 1	990	6/14/2013	6	6	18	5,483	Middle 3rd	28	**456.9**
Mix 2	1020	6/12/2013	6	6	18	4,341	Middle 3rd	28	**361.8**
Mix 3	1023	6/12/2013	6	6	18	3,039	Middle 3rd	28	**253.3**
Mix 4	1026	6/12/2013	6	6	18	4,359	Middle 3rd	28	**363.3**

A-3: WATER ABSORPTION AND UNIT WEIGHT

Core No.	WATER ABSORPTION AND UNIT WEIGHT						
	(1) SSD Weight (g)	(2) Wt in Air (g)	(3) ** Wt in Water (g)	(4) Percent Absorbed Water ((1-2)/2)x100	(5) Core Vol. (1/3)	(6) Core Bulk SG (2/5)	Core Unit Wt (pcf) (6)x62.4
987	3,348.10	2,959.80	1,816.10	12	1,532	1.9	120.6
988	3,677.90	3,411.20	2,032.70	7	1,645.20	2.1	129.4
989	3,666.50	3,451.50	2,059.60	6	1,606.90	2.1	134
990	3,642.60	3,314.80	2,042.80	9	1,599.80	2.1	129.3
991	3,673.60	3,407.20	2,066.10	7	1,607.50	2.1	132.3
992	3,280.20	2,914.10	1,800.70	11	1,479.50	2	122.9
1020	3,080.80	2,704.50	1,685.70	12	1,395.10	1.9	121
1021	3,325.70	3,013.30	1,889.50	9	1,436.20	2.1	130.9
1022	3,555.20	3,295.20	2,029.30	7	1,525.90	2.2	134.8
1023	3,151.70	2,841.70	1,764.90	10	1,386.80	2	127.9
1024	3,499.90	3,226.10	1,993.40	8	1,506.50	2.1	133.6
1025	3,592.40	3,224.10	2,009.30	10	1,583.10	2	127.1
1026	3234.2	2911.6	1,816.10	10	1,418.10	2.1	128.1
1027	3,347.40	3,014.70	1,899.90	10	1,447.50	2.1	130
1028	3,653.90	3,377	2,085.60	8	1,568.30	2.2	134.4

SSD- Saturated Surface Dry

A-4: VOID RATIO AND POROSITY RESULTS

Sample ID	A	B	C	D	E	F	G	H	I	J	SSD (g)	V_v	E (void ratio)	V_t	N (Porosity)
987	26.7	2960.8	1380.8	2960	110.9	0.67	1605.9	39.9	1566.0	1.89	3,348.10	387.3	25%	1,953.30	20%
988	49	3411.2	1745.6	3410.5	69.6	0.74	1713.9	66.2	1647.7	2.07	3,677.90	266.7	16%	1,914.40	14%
989	26.7	3451.5	1757.7	3450.3	129.3	0.64	1719.3	41.7	1677.6	2.06	3,666.50	215	13%	1,892.60	11%
990	49	3314.8	1672.7	3313.9	67.6	0.75	1690.2	65.3	1624.9	2.04	3,642.60	327.8	20%	1,952.70	17%
991	49	3407.2	1778.4	3401.7	69.5	0.74	1672.3	66.2	1606.1	2.12	3,673.60	266.4	17%	1,872.50	14%
992	49	2914.4	1330.9	2913.4	59.5	0.76	1631.5	64.5	1567.0	1.86	3,280.20	365.8	23%	1,932.80	19%
1020	49	2704.5	1133.4	2703.2	55.2	0.77	1618.8	63.6	1555.2	1.74	3,080.80	376.3	24%	1,931.50	19%
1021	49	3013.3	1396.9	3013.1	61.5	0.76	1665.2	64.5	1600.7	1.88	3,325.70	312.4	20%	1,913.10	16%
1022	49	3295.2	1536.6	3293.6	67.2	0.75	1806	65.3	1740.7	1.89	3,555.20	260	15%	2,000.70	13%
1023	49	2841.7	1236.1	2839.6	58.0	0.76	1652.5	64.5	1588.0	1.79	3,151.70	310	20%	1,898.00	16%
1024	49	3226.1	1536.9	3212.7	65.8	0.75	1724.8	65.3	1659.5	1.94	3,499.90	273.8	16%	1,933.30	14%
1025	49	3224.1	1580.1	3224	65.8	0.75	1692.9	65.3	1627.6	1.98	3,592.40	368.3	23%	1,995.90	18%
1026	49	2911.6	1318.5	2910.8	59.4	0.76	1641.3	64.5	1576.8	1.85	3,234.20	322.6	20%	1,899.40	17%
1027	49	3014.7	1385.8	3014.7	61.5	0.76	1677.9	64.5	1613.4	1.87	3,347.40	332.7	21%	1,946.10	17%
1028	49	3377	1727.8	3375.2	68.9	0.74	1696.4	66.2	1630.2	2.07	3,653.90	276.9	17%	1,907.10	15%

**Column A: bag weight (g)*
**Colum B: dry sample weight before sealing (g)*
**Column C: Sealed Sample weight in water (g)*
**Column D: Dry weight after water submersion (g)*
**Column E: Ration of Column B/Column A*
**Column F: Bag apparent gravity from CoreLok operator guide (pg. 24 and 25)*
**Column G: Total Volume Columns [(A-D)-C] (g)*
**Column H: Volume of bag Column (A/F) (g)*
**Column I: Volume of Sample (G-H) (g)*
**Column J: Bulk Specific Gravity (B/I)*
**SSD: Saturated Surface Dry*
**V_v: Volume of voids*
** V_t: Volume total*

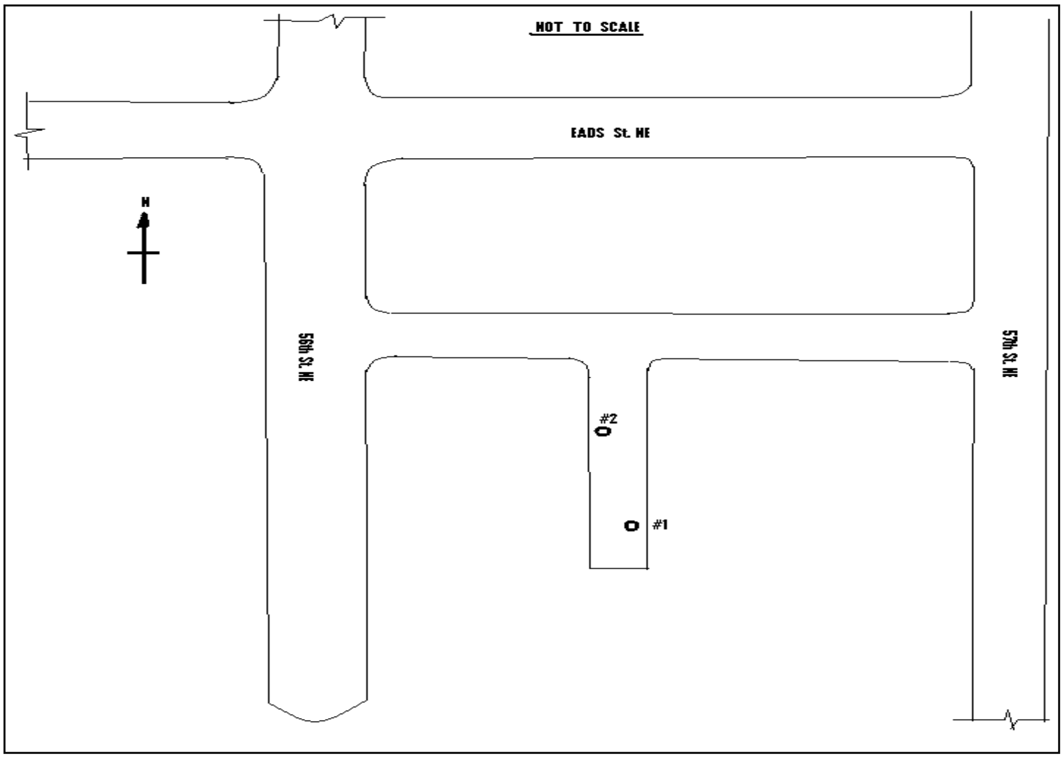
A-5: PERMEABLITY RESULTS

Mix Type	Core No.	Core Height (in)	Area (in^2)	t (hr)	Volume (in^3)	K (in/hr)	Average K (in/hr)
Control Mix	**987**	6.69	12.56	.017	572	304.69	**299.5**
		6.69	12.56	.017	553	294.79	
Control Mix	**988**	6.69	12.56	.017	114	60.67	**57.8**
		6.69	12.56	.017	103	55.07	
Control Mix	**989**	6.69	12.56	.017	152	81.18	**82.0**
		6.69	12.56	.017	156	82.95	
Mix 1	**990**	6.69	12.56	.017	204	108.83	**106.7**
		6.69	12.56	.017	196	104.68	
Mix 1	**991**	6.69	12.56	.017	146	77.86	**71.1**
		6.69	12.56	.017	121	64.41	
Mix 1	**992**	6.69	12.56	.017	582	310.23	**302.4**
		6.69	12.56	.017	554	295.08	
Mix 2	**1020**	6.69	12.56	.017	582	310.10	**299.6**
		6.69	12.56	.017	544	289.66	
Mix 2	**1021**	6.69	12.56	.017	399	212.76	**202.5**
		6.69	12.56	.017	361	192.49	
Mix 2	**1022**	6.69	12.56	.017	192	102.35	**90.7**
		6.69	12.56	.017	149	79.18	
Mix 3	**1023**	6.69	12.56	.017	405	215.61	**209.7**
		6.69	12.56	.017	383	204.22	
Mix 3	**1024**	6.69	12.56	.017	32	17.00	**83.4**
		6.69	12.56	.017	281	149.86	
Mix 3	**1025**	6.69	12.56	.017	216	114.88	**107.9**
		6.69	12.56	.017	190	101.16	
Mix 4	**1026**	6.69	12.56	.017	532	283.30	**291.4**
		6.69	12.56	.017	563	299.92	
Mix 4	**1027**	6.69	12.56	.017	440	234.26	**224.9**
		6.69	12.56	.017	405	215.91	
Mix 4	**1028**	6.69	12.56	.017	277	147.71	**136.5**
		6.69	12.56	.017	236	125.49	

FIELD INFILTRATION TESTS OF PERMEABLE PAVEMENTS IN DC

Location 1: Alley between 56th and 57th Street Bounded by Eads Street NE

Test Date: 10/09/2013



Inside Diameter of infiltration ring (in) = 12.25

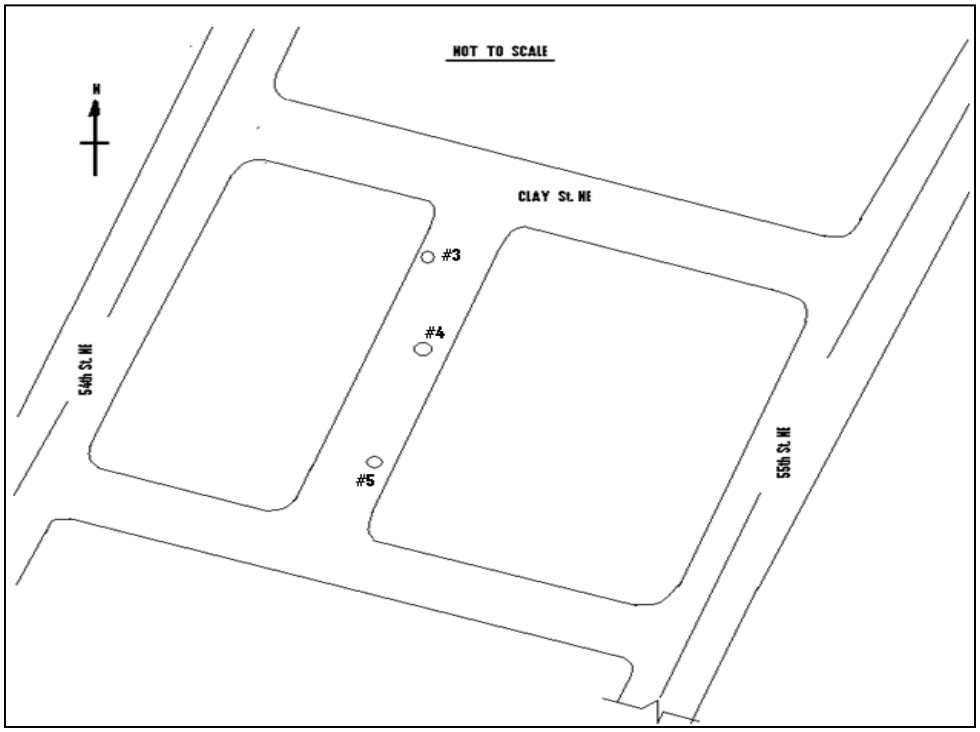
K = 126,870 in

A-6: Field Infiltration Test at Location 1

Location #	Time required (s)	Mass of infiltrated water (lb)	Infiltration rate (in/hr)
1	377	40	89.7
2	410	40	82.5

Location 2: Alley between 54th and 55th Street Bounded by Clay Street NE

Test Date: 10/09/2013



Inside Diameter of infiltration ring (in) = 12.25

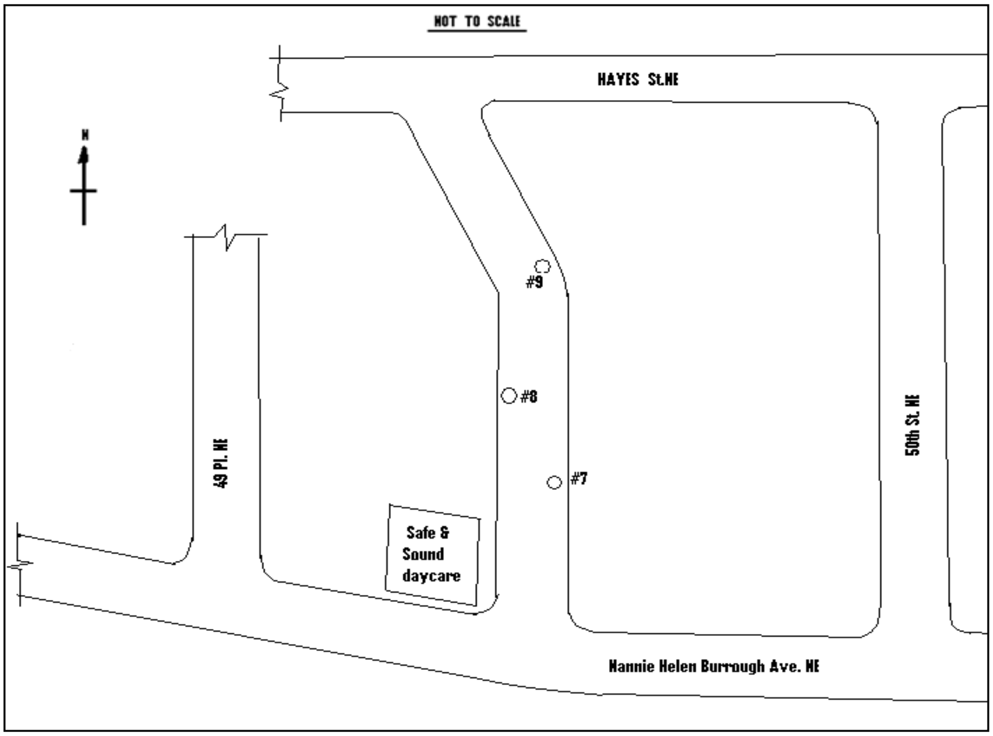
K = 126,870 in

A-7: Field Infiltration Test at Location 2

Location #	Time required (s)	Mass of infiltrated water (lb)	Infiltration rate (in/hr)
3	62	8	109.1
4	142	40	238.2
5	72	8	93.9

Location 3: Alley between 49th and 50th Street Bounded by Nannie Helen Burrough Ave, NE

Test Date: 10/09/2013



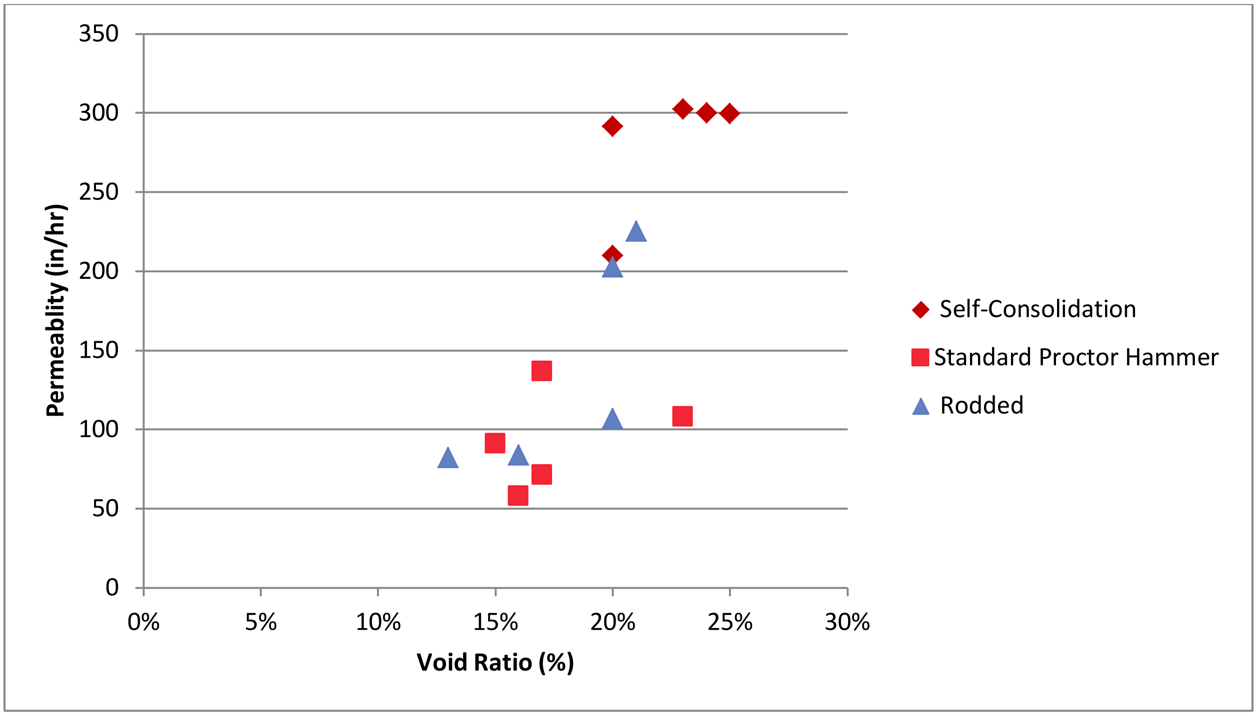
Inside Diameter of infiltration ring (in) = 12.25

K = 126,870 in

A-8: Field Infiltration Test at Location 3

Location #	Time required (s)	Mass of infiltrated water (lb)	Infiltration rate (in/hr)
7	97	40	348.6
8	34	8	198.9
9	86	8	78.7

PLOTS OF SAMPLE PROPERTIES



Permeability with Percent Voids for Self-Consolidation, Proctor Hammer, and Rodded Samples