Optimal Mix Designs for Pervious Concrete for anUrban Area

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***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 provides larger air void than conventional concrete to increase the rate of infiltration. Most jurisdictions have different pervious concrete mix designs. 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 for the District of Columbia. 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 57.8 inches per hour (in/hr) was identified as the optimum. The maximum modulus of rupture of the selected mix was determined to be 565 psi. In-situ infiltration tests conducted of the pervious concrete installed at 3 locations in DC with the optimal pervious concrete mix yielded average infiltration rates between 86.1 and 208.7 in/hr.**

Keywords—Pervious Concrete,porosity, porous,mix design, permeability, stormwater

I. 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 to identify the optimal pervious concrete mix design. A presumedoptimal permeable concrete design mix was used as the basis (control mix) for this study. This research conducted laboratory tests on five pervious concrete mix designs in order to identify the optimum mix. In situ infiltration tests were also conducted to determine the infiltration rate. The findings of this research will enable DDOT to prepare pervious concrete mixes with acceptable properties.

II. 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 needed to be investigated. As a result, the objectives of this research were:

- Develop and test five pervious concrete design mixes (including the control mix)
- Recommend the optimal mix based on the results of the tests.

III. 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).

Scholz et al., 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.

An experiment was 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).

In 2003, a long term study of stormwater quantity and performance of permeable pavement systems was launched which 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).

Iowa State University conducted a study in 2008 which summarized the results of 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 results 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).

In the same study, the researchers used the self-consolidating method to prepare the pervious concrete. That method used 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).

The optimum soil conditions that could improve infiltration rates of pervious pavementswas investigated in 2009. Four types of soil conditions were studied: no treatment of soil, trenched-soil trenched, ripped- subsoil, and boreholes. The research used23 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)

In a 2010 study conducted 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 et al., 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 inseveral field tests which vary based on the underlying soil characteristics and/or jurisdiction. Several studies indicate that pervious concreteallows water to infiltrate at very high rates, typically from 100 to 200 in/hr.

IV. Research Methodology and Data Collection

The first part of this study focused on testing pervious concrete mix designs to determinethe mix with the optimal compressive strength, flexural strength, and permeability.Four design mixes were tested and compared with a control mix. 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.Consolidation of the specimen was conducted in 3 different ways: self-consolidating, rodded, and Proctor Hammer.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.

A. 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 I.

B. 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:

1) Self-Consolidating (SC): also referred to as self-compacting. The cylinder was completely filled and struck and capped under pressure.
2) 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.
3) 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

C. 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 Fig. 1.An example of a failed sample is presented in Fig. 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 IIpresents the temperature and unit weights of the five samples.

D. 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

$$M_R = (P*L)/(B*D^2) \quad (1)$$

where P is the load (force) at the fracture point, L is the span length (distance between supports), B is the width, D is the thickness.

TABLE I. PERVIOUS CONCRETE MIX DESIGN

Mix Design	Control Mix	Mix 1	Mix 2	Mix 3	Mix 4
Cement, Holcim	29.64 lb	29.64 lb	29.64 lb	29.64 lb	29.64 lb
Fly Ash	8.52 lb	8.52 lb	8.52 lb	8.52 lb	8.52 lb
#8 Stone (Millville)	208.8 lb	206.9 lb	205.1 lb	203.2 lb	201.4 lb
Sand (Howlin)	5.56 lb	7.41 lb	5.56 lb	11.12 lb	12.97 lb
Water	13 lb	13 lb	13 lb	13 lb	13 lb
HRWR	0.22 lb	-	-	-	-
Hydromax (Internal curing Ad-mixture)	0.11 lb	-	-	-	-
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

Fig. 1. Concrete cylinder placed in loading frame

Fig. 2. A sample of failed pervious concrete

TABLE II. 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

E. 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 Fig. 3.

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. Fig. 4 is a sample of sealed perviousconcrete that was placed in the Corelok.

Fig. 3. Corelok

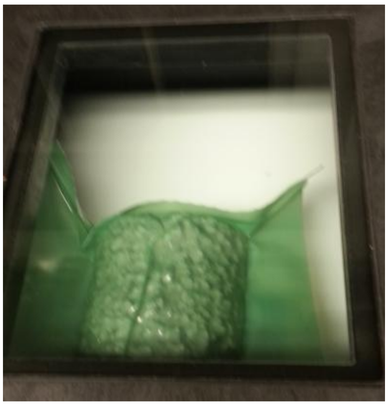

Fig. 4. A sealed pervious concrete sample placed in Corelok

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

$$e = V_v/V_s \qquad (2)$$

where e is the void ratio, V_v is the volume of voids, and V_s is the volume of solids

$$n = V_v/V_t \qquad (3)$$

where$n$ is the porosity, V_v is the volume of voids and V_t is the total volume.

F. *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:

$$K= (Q*L)/(A*t*h) \qquad (4)$$

where Q is the volume, L is the length, A is the area, t is the time, and h is the head.

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

V. RESULTS

A. *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 III presents the results of the 7-day and 28-day compressive strengths for each mix design.

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.

TABLE III. 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

B. *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 Fig. 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.

C. *Voids*

Table IV presents the results of the percent voids in the pervious concrete mixes for the self-consolidating, rodded, andProctor 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%.

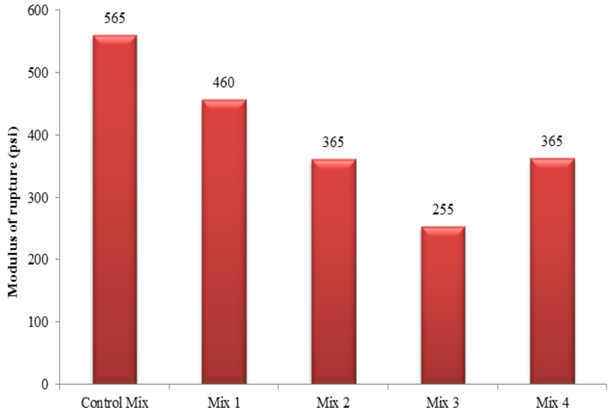

Fig. 5. Modulus of rupture for pervious concrete (28-day cured)

TABLE IV. 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**

TABLE V. 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

TABLE VI. 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

VI. 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.

VI. IN-SITU INFILTRATION TESTS

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 was installed (as shown in Fig. 6). The ring was secured in place with plumber’s putty after which the concrete is pre-wet with 8 pounds of water.

Fig. 6. Single-ring infiltrometer (ASTM C1701)

The head of water between the two marks on the interior of the ring was maintained throughout the test. A time clock wasstarted as soon as the water is poured on to the pervious concrete until there was 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.

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

$$K = (kM)/(D^2*t) \qquad (5)$$

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.

The infiltration rates of the pervious concrete installed at 3 locations in DC were obtained in the field using the procedures mentioned. A minimum of 2 locations per pervious concrete section should be tested.

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 thetypical infiltration rate range of pervious concrete (i.e.,100 to 200in/hr).

VII. 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. The control design mix 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 appears to be the optimum procedure for preparing the pervious concrete.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 thetypical infiltration rate range of pervious concrete (i.e.,100 to 200in/hr).

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

- Consider a pilot 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.

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