ACI MATERIALS JOURNAL TECHNICAL PAPER

Title no. 107-M71

Effect of Aggregate Size and Gradation on Pervious Concrete Mixtures

by Andrew I. Neptune and Bradley J. Putman

*The purpose of this research was to determine the effects of aggregate size and gradation on the unit weight, strength, porosity, and permeability of pervious concrete mixtures. The water-cement ratio (*w/c*) and cement-aggregate ratio (*c/a*) were kept constant at 0.29 and 0.22, respectively, with a design unit weight of 2002 kg/m*^{3}*(125 lb/ft*^{3}*). Fifteen different aggregate gradations were tested and categorized according to nominal maximum aggregate sizes (NMASs) of 9.5, 12.5, and 19.0 mm (0.38, 0.49, and 0.75 in.) and had a range of uniformity coefficients* C_u*. The results indicated that as the porosity increased, strength decreased and permeability increased. In general, as the* C_u *of the aggregate increased—that is, the gradation became less uniform or single-sized and more well-graded—the strength also increased, whereas the porosity and permeability decreased. There appeared to be an optimum/pessimum* C_u *range in which the strength of the pervious concrete reached a maximum and the permeability reached a minimum.*

Keywords: aggregate gradation; permeability; pervious concrete; porosity; porous pavement; uniformity coefficient.

INTRODUCTION

Pervious concrete is considered a best management practice (BMP) because of its capability to reduce excessive storm-water runoff (Bury et al. 2006). Its porous structure allows both water and air to percolate through its matrix into the subsoils beneath. Because of its interconnected pores, pervious concrete reduces runoff but also filters by entrapping contaminants (for example, chemicals and particulates) on and within the pervious concrete structure (Schaefer et al. 2006). The size of these pores is affected by the gradation and type of the aggregate in the mixture, the quantity of water and cement added, and the level of compaction.

Studies conducted on pervious concrete have emphasized examining primarily single-sized aggregate. Although the greatest concern regarding pervious concrete is permeability, which is maximized with the use of single-sized aggregate, the strength of the structure cannot be overlooked. The use of pervious concrete is application-specific; some cases may require high permeability mixtures depending on the rainfall intensity in a location, whereas strength may be the governing factor for others.

It is an accepted fact that pervious concrete is lower in strength compared with conventional concrete mixtures, hence the reason for its application in low-traffic roads, parking lots, driveways, and sidewalks (Tennis et al. 2004). Durability tests conducted on pervious concrete specimens, however, have shown that the addition of 7% fine aggregate to the mixture improved strength by 57 to 84% but reduced void ratios by 6 to 8% (Kevern et al. 2005). With consideration given to these results and others alike, it may be necessary to use both distributed sizes and single-sized aggregate to prepare pervious concrete batches in an effort to help engineers design gradations that optimize both hydrologic and strength properties.

Table 1—Summary of aggregate properties

Test description	ASTM designation	Coarse aggregate
Absorption, %	C127	0.6
Los Angeles abrasion, % loss	C131 (Grade B)	52
Specific gravity, bulk	C127	2.65
Specific gravity, saturated surface dry	C127	2.66
Specific gravity, apparent	C127	2.69

RESEARCH SIGNIFICANCE

The focus of previous research on pervious concrete mixtures has primarily been on optimizing hydrologic properties. As a result, single-sized aggregates were used. Although permeability may be the greatest concern in one application because of high rainfall intensities, another application may place greater emphasis on strength while maintaining a certain level of permeability. Therefore, the main objective of this study was to investigate the effects of aggregate gradation on the performance of pervious concrete mixtures. Aggregate gradation can potentially be a predictor of pervious concrete performance in an effort to satisfy site-specific requirements.

EXPERIMENTAL PROCEDURE

Pervious concrete mixtures require a careful analysis of aggregate size distribution and properties for a pavement to be capable of bearing expected loads and allowing water to drain through its matrix at a suitable rate. Another function of pervious concrete pavements relates to its filtering capabilities and the duration of acceptable performance before it clogs with silt or debris. Considering these variables, the pervious concrete in this study was prepared using 15 different aggregate gradations with three nominal maximum aggregate sizes (NMASs).

Materials

One crushed granite aggregate source was used in this study (refer to Table 1). The gradation specifications used in this research were taken from the requirements of ASTM C33/C33M-08 (ASTM 2008), ASTM D448-08 (ASTM 2008), and typical asphalt open-graded friction course specifications (GDOT 2003). The cement used in this

---

ACI Materials Journal, V. 107, No. 6, November-December 2010.

MS No. M-2010-027 received January 25, 2010, and reviewed under Institute publication policies. Pertinent discussion including authors' closure, if any, will be published in the September-October 2011 *ACI Materials Journal* if the discussion is received by June 1, 2011.

Andrew I. Neptune *is a Graduate Student in the Department of Civil Engineering at Clemson University, Clemson, SC. He is currently working on his PhD in civil engineering at Clemson University with an emphasis on construction materials. He received his BS in engineering science from Bob Jones University, Greenville, SC, and his MS in civil engineering from Clemson University.*

ACI member **Bradley J. Putman** *is an Assistant Professor in the Department of Civil Engineering at Clemson University. He received his BS, MS, and PhD in civil engineering from Clemson University. His research interests include construction materials and pavements with a focus on sustainable pavements.*

Table 2—Categorization of aggregate gradations and proportions according to NMAS of 9.5 mm (0.38 in.)

	A	B	C	D	E
Sieve size, mm (in.)	Percent passing, %	Percent passing, %	Percent passing, %	Percent passing, %	Percent passing, %
25.4 (1)	100	100	100	100	100
19.0 (0.75)	100	100	100	100	100
12.5 (0.5)	100	100	100	100	100
9.5 (0.38)	100	90	93	95	100
4.75 (No. 4)	0	20	30	34	53
2.36 (No. 8)	0	5	7	13	26
1.18 (No. 16)	0	0	0	0	0
D_{10}, mm	5.1	3.0	2.6	2.0	1.6
D_{60}, mm	7.2	7.0	6.6	6.4	5.3
C_u	1.41	2.34	2.53	3.20	3.28
DRUW,* kg/m^3	1538	1602	1634	1634	1586

*DRUW is dry-rodded unit weight.
Note: 1 kg/m^3 = 0.0624 lb/ft^3; 25.4 mm = 1 in.

project was general-purpose Type I portland cement meeting the requirements of ASTM C150/C150M-09 (ASTM 2009).

Methods—mixture design

The mixture design for each pervious concrete batch had a target unit weight of 2002 kg/m^3 (125 lb/ft^3) and a cement-aggregate ratio (*c/a*) of 0.22 as recommended by Tennis et al. (2004). A water-cement ratio (*w/c*) of 0.29 (exclusive of aggregate absorption) was determined from preliminary testing. This design resulted in mixture proportions of 96 kg (212 lb) of water, 352 kg (776 lb) of cement, 1554 kg (3426 lb) of aggregate, and 21% air content (theoretical) for a 1 m^3 (1.3 yd^3) batch of concrete. The *w/c* was kept constant throughout this study, which led to the assumption that a mixture that was pasty in nature—that is, noticeably wetter—was an indication of lower water demand. This was observed in aggregate gradations that consisted of a higher proportion of larger-sized coarse aggregate.

Methods—aggregate proportioning

The aggregate gradations used in this study were categorized into three groups based on common NMASs. The NMAS used in this study was defined as one size larger than the first sieve to have less than 90% passing. The different gradations within each group varied by coefficient of uniformity C_u (Eq. (1)) to provide a relatively wide range of gradations while maintaining an open-graded structure to allow water to flow through the concrete. The aggregate gradations were also categorized by D_{10}, D_{60}, and the dry unit weight values, as shown in Tables 2 through 4.

Table 3—Categorization of aggregate gradations and proportions according to NMAS of 12.5 mm (0.5 in.)

	F	G	H	I	J	K
Sieve size, mm (in.)	Percent passing, %	Percent passing, %	Percent passing, %	Percent passing, %	Percent passing, %	Percent passing, %
25.4 (1)	100	100	100	100	100	100
19.0 (0.75)	100	100	100	100	100	100
12.5 (0.5)	100	90	100	95	92	100
9.5 (0.38)	0	40	85	58	65	75
4.75 (No. 4)	0	5	20	15	20	25
2.36 (No. 8)	0	0	5	5	8	10
1.18 (No. 16)	0	0	0	0	0	0
D_{10}, mm	9.8	5.3	3.0	3.4	2.8	2.4
D_{60}, mm	11.8	10.9	7.3	9.7	8.8	7.8
C_u	1.20	2.07	2.43	2.83	3.18	3.23
DRUW,* kg/m^3	1586	1618	1634	1634	1666	1634

*DRUW is dry-rodded unit weight.
Note: 1 kg/m^3 = 0.0624 lb/ft^3; 25.4 mm = 1 in.

Table 4—Categorization of aggregate gradations and proportions according to NMAS of 19.0 mm (0.75 in.)

	L	M	N	O
Sieve size, mm (in.)	Percent passing, %	Percent passing, %	Percent passing, %	Percent passing, %
25.4 (1)	100	100	100	100
19.0 (0.75)	100	100	100	100
12.5 (0.5)	0	77	66	85
9.5 (0.38)	0	55	38	55
4.75 (No. 4)	0	0	5	15
2.36 (No. 8)	0	0	3	5
1.18 (No. 16)	0	0	0	0
D_{10}, mm	14.0	5.4	5.3	3.5
D_{60}, mm	16.9	10.1	12.6	10.0
C_u	1.20	1.87	2.36	2.89
DRUW,* kg/m^3	1602	1618	1650	1650

*DRUW is dry-rodded unit weight.
Note: 1 kg/m^3 = 0.0624 lb/ft^3; 25.4 mm = 1 in.

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

where D_{60} is the diameter of aggregate corresponding to 60% finer and D_{10} is the diameter of aggregate corresponding to 10% finer.

Methods—mixing and curing techniques

The mixing and curing procedures were performed in accordance with ASTM C192/C192M-07 (ASTM 2007) with one adjustment. This adjustment included the addition of approximately 5% of the cement to the aggregate, which was allowed to mix for 1 minute to initiate the coating of the aggregate with the cement and improve bonding (Schaefer et al. 2006). Each pervious concrete batch size was approximately 0.024 m^3 (0.83 ft^3) and was prepared in a concrete mixer capable of mixing 0.042 m^3 (1.5 ft^3) of concrete per batch.

A total of 300 specimens were made for this study, not including those prepared for preliminary studies. Of these 300 specimens, 225 were cylinders 76.2 mm (3 in.) in diameter and 152.4 mm tall (6 in.), and 75 were prisms 76.2 x 76.2 x 304.8 mm (3 x 3 x 12 in.). These specimens were consolidated by rodding in accordance with the procedures outlined in ASTM C192/C192M-07 (ASTM 2007) and vibration (10 seconds on a vibrating table with a setting of five out of 10 after rodding). The freshly consolidated concrete specimens were covered with plastic and placed in a curing room equipped with a sprinkler that generated a constant mist and maintained a temperature of approximately 23.7°C (73.4°F). After 24 ± 8 hours, the specimens were removed from their molds and kept in the curing room until 28 days had passed since casting.

Methods—testing

Prior to specimen casting, the fresh unit weight (ASTM C138/C138M-10a [ASTM 2010]) was measured for each pervious concrete mixture immediately after mixing using both the rodding and jigging procedures outlined in ASTM C29/C29M-09 (ASTM 2009). The actual density of the mixture was determined and a typical tolerance of ±80 kg/m^3 (±5 lb/ft^3) of the designed unit weight was implemented based on the literature review (NRMCA 2004). The density or bulk specific gravity G_{mb} of hardened pervious concrete specimens was determined using methods developed for open-graded asphalt mixtures. The CoreLok® system, in accordance with ASTM D6752-09 (ASTM 2009), was used to seal the pervious concrete cylindrical specimens in a polymeric bag. Prior to sealing, air was removed from the bag using the CoreLok vacuum pump. This process allows for the measurement of the density of a porous material using standard water displacement methods.

The porosity of the hardened concrete specimens was measured in accordance with ASTM D7063 (ASTM 2005). Again, this procedure uses the CoreLok system and was developed for measuring the effective porosity of asphalt materials. The effective porosity of a specimen is the total amount of interconnected voids that allows water to saturate the specimen from its surfaces (Eq. (2))

$$\%\ \text{effective porosity} = \frac{\text{ASG} - \text{BSG}}{\text{ASG}} \times 100 \qquad (2)$$

where ASG is the apparent specific gravity and BSG is the bulk specific gravity.

The standard compressive, split-tensile, and flexural strength tests were performed on the relevant specimens as documented in ASTM C39/C39M-09a (ASTM 2009), ASTM C496/C496M-04 (ASTM 2004), and ASTM C78/C78M-10 (ASTM 2010), respectively. A total of 20 specimens were made of each specific aggregate gradation. Of the 20 specimens, five were beams used for flexural strength testing and the remainder were cylinders. The cylindrical specimens were leveled for testing by sawing 6.35 mm (0.25 in.) off the top ends. The new heights, along with the diameters of the cylinder, were measured and recorded for computational purposes.

One of the most crucial tests used in the selection of an aggregate gradation that qualifies for pervious concrete mixtures is the permeability test. The lack of standardized specifications has allowed room for innovative techniques to measure this criterion. The literature review revealed that it was common practice to use a falling-head apparatus to measure permeability (Yang and Jiang 2003; Kevern et al. 2005). An arrangement of the falling-head permeability test used in this research is shown in Fig. 1.

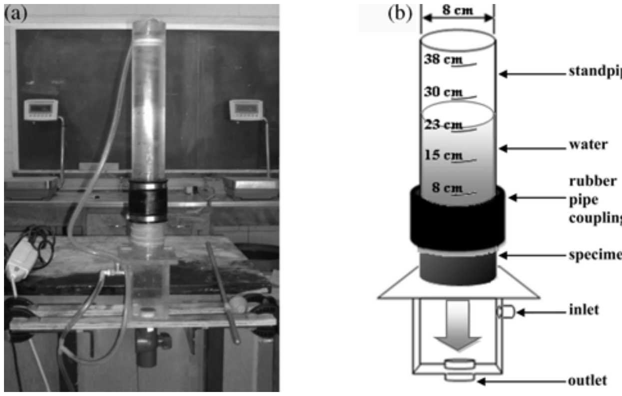

Fig. 1—Falling-head permeability test setup: (a) photograph; and (b) schematic. (Note: 1 cm = 0.3937 in.)

The preparation of each specimen for the permeability test first involved sawing off 19.0 mm (0.75 in.) from each end of the specimen, resulting in a total height of 114.3 mm (4.5 in.). The sides of the specimen were then sealed off with petroleum jelly to prevent water from flowing out the sides. The specimens were then slid into a rubber membrane and rubber bands were used on the outside of this membrane at the bottom, middle, and top to prevent slippage and potential leakage along the sides. The sealed sample was placed into the specimen holder at the bottom of the standpipe. The standpipe was attached to the specimen holder by a rubber pipe coupling. The standpipe had an inside diameter of 76.2 mm (3 in.) and had 76.2 mm (3 in.) divisions marked down the front. Water was then pumped into the bottom chamber and allowed to saturate the pervious concrete specimen to a level above the specimen, after which the side valve was closed and the standpipe was filled. The water was allowed to flow through the specimen by opening the bottom valve. At an initial head of 305 mm (12 in.) above the specimen, the time was started and recorded when the water level reached a final head of 76.2 mm (3 in.) above the specimen. This process was repeated four times for each specimen to allow for flushing of the specimen pores. The permeability k of the specimens was calculated using Eq. (3) (Das 2001)

$$k = \frac{aL}{At}\log_e, \frac{h_1}{h_2} \qquad (3)$$

where k is the permeability, a is the cross-sectional area of the standpipe, L is the length of the specimen, A is the cross-sectional area of the pervious concrete specimen, t is the duration of flow, h_1 is the initial head difference, and h_2 is the final head difference.

STATISTICAL ANALYSIS OF EXPERIMENTAL RESULTS

Statistical analysis software (SAS) was used to compare the strength, porosity, and permeability values of the

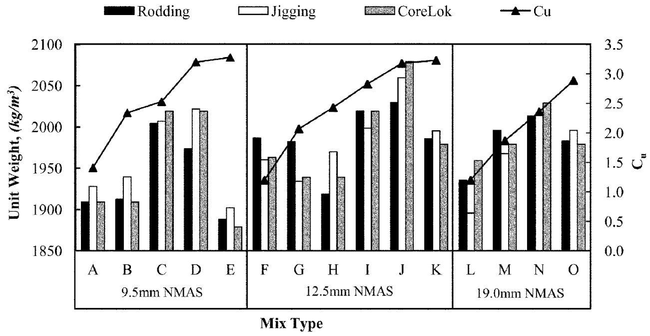

Fig. 2—Comparison of unit weights by rodding and jigging of fresh concrete mixtures and CoreLok computations of hardened pervious concrete specimens. (Note: 1 kg/m^3 = 0.0624 lb/ft^3; 1 mm = 0.03937 in.)

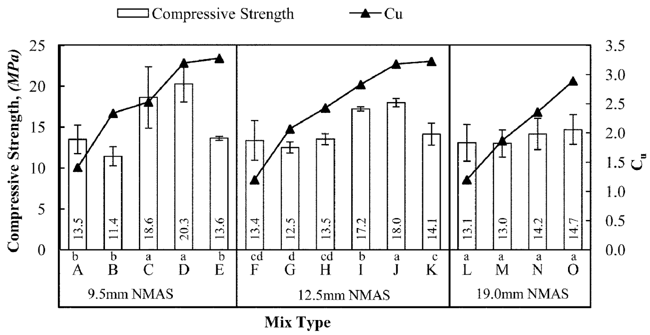

Fig. 3—Compressive strength for pervious concrete specimens grouped according to NMAS. Mixtures within each NMAS with at least one lowercase letter (indicated above mixture label) in common have values that are statistically similar for α = 0.05. Error bars indicate one standard deviation. (Note: 1 MPa = 145.04 psi; 1 mm = 0.03937 in.)

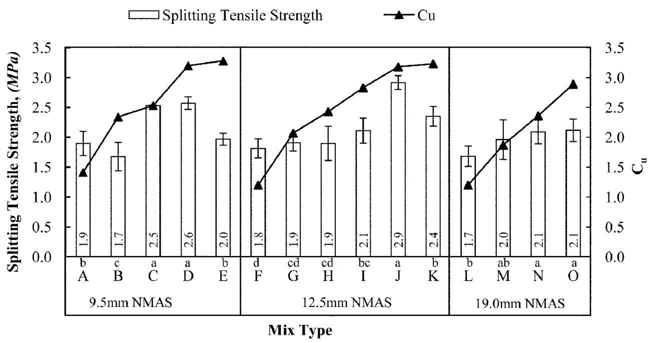

Fig. 4—Split-tensile strengths for pervious concrete specimens grouped according to NMAS. Mixtures within each NMAS with at least one lowercase letter (indicated above mixture label) in common have values that are statistically similar for α = 0.05. Error bars indicate one standard deviation. (Note: 1 MPa = 145.04 psi; 1 mm = 0.03937 in.)

pervious concrete mixtures within the respective NMAS. An analysis of variance (ANOVA) was first conducted to determine if any differences existed between the mixtures (α = 0.05). This was then followed by Fisher's *t*-test for least significant difference to determine which mixtures had significantly different properties within the treatment group (that is, NMAS). Differences are indicated in the respective figures with the use of letters. Mixtures in a specific NMAS category with at least one common lowercase letter located above the mixture labels exhibited statistically similar values and those with no common letters had values that were not significantly similar at α = 0.05.

EXPERIMENTAL RESULTS AND DISCUSSION

Pervious concrete unit weight

One of the key factors of a fresh pervious concrete mixture is the unit weight. Because there has been relatively limited research conducted on pervious concrete, there is no officially standardized test procedure to measure unit weight, except procedures published by individual researchers. The unit weight, however, is one of the best available measures for quality control of pervious concrete mixtures. Field practices have since determined that the acceptance of a pervious concrete mixture rests on a tolerance factor of ±5% or 80 kg/m^3 (5 lb/ft^3) of the design unit weight (Tennis et al. 2004). As a result of the emphasis placed on the unit weight, two methods of compaction were analyzed in this study: rodding and jigging.

There are different methods of compacting concrete for the standard unit weight test. Although it is a regular practice to compact pervious concrete by jigging in accordance with ASTM C29/C29M-09 (ASTM 2009) and the National Ready Mixed Concrete Association (NRMCA 2004), an alternative method of compaction—rodding—was investigated to understand its effect on determining unit weight. ASTM C138/C138M-10a (ASTM 2010) recommends rodding for concrete with slumps of 75 mm (3 in.) or greater and vibration for concrete with slumps of less than 25 mm (1 in.). The fact that pervious concrete is not considered to have a slump and that its composition is different from regular concrete (that is, it has no fines), could possibly be a reason why rodding is not regularly practiced in measuring the unit weight of pervious concrete mixtures. ASTM C29/C29M-09 (2009) recommends jigging to compact aggregates with a nominal maximum size ranging from 37.5 to 125 mm (1.5 to 5 in.). The differences between unit weights from the two methods of compaction were quite small for the most part, as shown in Fig. 2. Generally, jigging resulted in higher unit weights for all of the mixtures within the 9.5 mm (0.38 in.) gradation and mixtures with C_u values of closer to 3.0 and above. On the other hand, the rodding procedure produced higher values for the mixtures with lower C_u values in the 12.5 and 19.0 mm (0.5 and 0.75 in.) NMAS mixtures.

Figure 2 also compares the fresh unit weight results to the hardened concrete unit weight determined using the CoreLok method. The CoreLok method followed the unit weight trends of the fresh concrete, and the CoreLok results were closer to the rodding procedure for fresh concrete in eight out of 15 mixtures compared to five out of 15 mixtures for jigging. The remaining two mixtures had similar values for unit weight determined by rodding and jigging. This trend, however, was not consistent with C_u or NMAS.

Pervious concrete strength analysis

The pervious concrete strength tests conducted in this study included compression, split-tensile, and flexural strength tests. After the specimens were tested, they were examined, and it was observed that the majority of the failures occurred because of the aggregate fracture and not because of fracturing of the cement paste.

Figures 3 through 5 summarize the results of the compressive, split-tensile, and flexural strengths, respectively, of the pervious concrete mixtures. Based on the results, it is evident that the C_u of the aggregate gradation had a significant effect on all three strength properties. For the 9.5 and 12.5 mm (0.38 and 0.5 in.) NMAS categories, the strength increased with the C_u to a point (approximately 3.2), at which it then decreased. The 19.0 mm (0.75 in.) NMAS mixtures did not show this decrease in strength, possibly because the C_u did not exceed 2.89 for this group.

When comparing the effect of aggregate NMAS on the strengths, there was not a large discrepancy. The ranges in strength within each nominal maximum aggregate size grouping were quite similar. If one were to use a compressive strength of 13.8 MPa (2000 psi) as a cutoff for compressive strength, however, then there were two mixtures (Mixtures C and D) with an NMAS of 9.5 mm (0.38 in.), three mixtures (Mixtures I, J, and K) with an NMAS of 12.5 mm (0.5 in.), and two mixtures (Mixtures N and O) with an NMAS of 19.0 mm (0.75 in.) that met the requirement (Fig. 3). It should be noted that six of the remaining eight mixtures had compressive strengths within 6% below 13.8 MPa (2000 psi).

Additionally, the results indicated a correlation between the compressive and flexural strengths of the pervious concrete mixtures included in this study that was similar to the correlation that exists in normal concrete (Mindess et al. 2002). This correlation is important in the estimation of the flexural strength of a concrete mixture, especially in cases in which only cylinders are available for compression testing. The expected trend of flexural strength increasing as compressive strength increased was established in the results. Figure 6 shows the correlations that exist between the compressive and flexural strengths of the pervious concrete mixtures from this study. The relationships between 28-day flexural strength R and the compressive strength f_c' of the pervious concrete mixtures were developed from the test results

$$R = 0.63(f_c')^{0.47} \text{ (MPa)} \qquad (4)$$

$$R = 8.73(f_c')^{0.47} \text{ (psi)}$$

where R is the flexural strength and f_c' is compressive strength.

The relationship was quite similar to the relationship between flexural and compressive strength for conventional concrete (Mindess et al. 2002).

$$R = 0.62(f_c')^{0.5} \text{ (MPa)} \qquad (5)$$

$$R = 7.5(f_c')^{0.5} \text{ (psi)}$$

Figure 6 also shows the relationship between compressive and split-tensile strength for the pervious concrete mixtures included in this study. Again, the expected trend of increasing split-tensile strength with compressive strength was observed

$$T = 0.22(f_c')^{0.84} \text{ (MPa)} \qquad (6)$$

$$T = 0.49(f_c')^{0.84} \text{ (psi)}$$

where T is the split-tensile strength and f_c' is compressive strength.

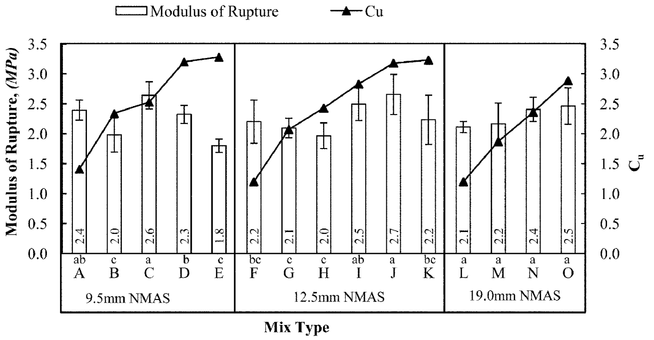

Fig. 5—Flexural strengths for pervious concrete specimens grouped according to NMAS. Mixtures within each NMAS with at least one lowercase letter (indicated above mixture label) in common have values that are statistically similar for α = 0.05. Error bars indicate one standard deviation. (Note: 1 MPa = 145.04 psi; 1 mm = 0.03937 in.)

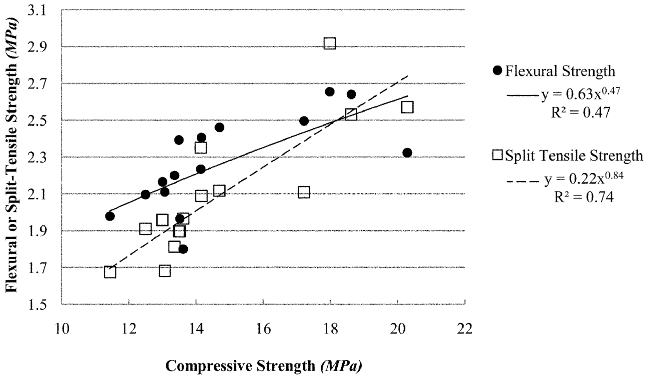

Fig. 6—Correlation between compressive strength and flexural and split-tensile strength for pervious concrete. (Note: 1 MPa = 145.04 psi.)

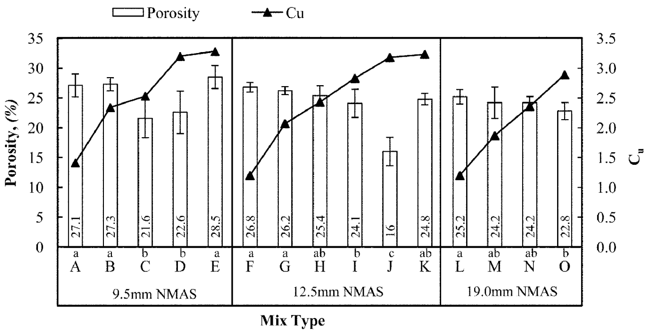

Fig. 7—Porosity of pervious concrete mixtures grouped according to NMAS. Mixtures within each NMAS with at least one lowercase letter (indicated above mixture label) in common have values that are statistically similar for α = 0.05. Error bars indicate one standard deviation. (Note: 1 mm = 0.03937 in.)

Effective porosity of pervious concrete mixtures

Effective porosity is the percentage of water-accessible air voids situated throughout a compacted specimen (refer to ASTM D7063 [ASTM 2005]). The mixture design for this study revealed a theoretical air content of 21% for the pervious concrete mixtures. The CoreLok test generated porosity results ranging from 16 to 28.5%. Figure 7 illustrates the relationship between the effective porosity and the C_u. The

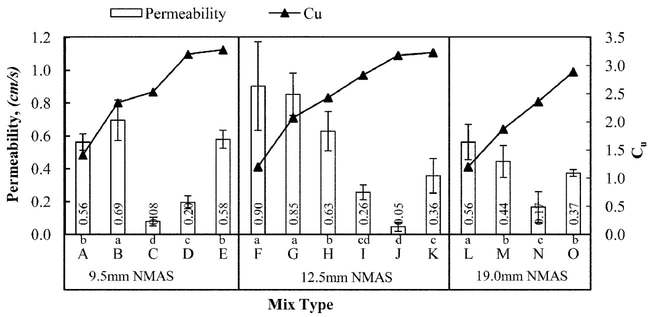

Fig. 8—Permeability of pervious concrete mixtures with head difference of 30.5 cm (12 in.) grouped according to NMAS. Mixtures within each NMAS with at least one lowercase letter (indicated above mixture label) in common have values that are statistically similar for $\alpha = 0.05$. Error bars indicate one standard deviation. (Note: 1 cm/s = 1417 in./h.; 1 mm = 0.03937 in.)

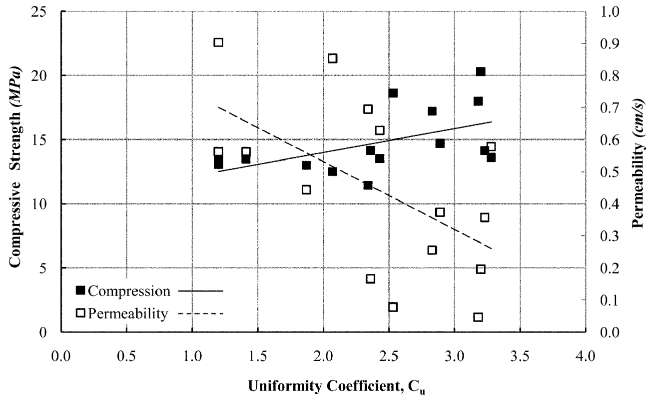

Fig. 9—Relationship between compressive strength, permeability, and uniformity coefficient. (Note: 1 MPa = 145.04 psi; 1 cm/s = 1417 in./h.)

expected trend of the effective porosity decreasing as the C_u increased was not dramatically evident within all of the different NMASs. The trend was opposite of that of the strengths, in that the effective porosity decreased as the C_u increased to a point at which the porosity then increased. It should be noted that the turning point coincided with that of the pervious concrete strength. As with the strength results, the 19.0 mm (0.75 in.) NMAS mixtures did not show the turning point C_u, which again is potentially due to the fact that the range of C_u values did not reach the turning point of approximately 3.2.

Permeability of pervious concrete mixtures

The permeability of the pervious concrete mixtures is illustrated in Fig. 8. The pervious concrete mixtures that were expected to possess the highest permeability values were those prepared from single-sized aggregates—that is, the lowest C_u. This was generally observed in all of the categories, with the exception of Mixture A with an NMAS of 9.5 mm (0.38 in.), which had a slightly lower permeability than the highest in the group. The more well-graded a mixture was—that is, the higher its C_u—the lower its permeability. As with the effective porosity, the trends were opposite those of the concrete strength. There was a general decrease in permeability with increasing C_u to a turning point at which the permeability increased. The turning points were similar to those observed for strength and porosity.

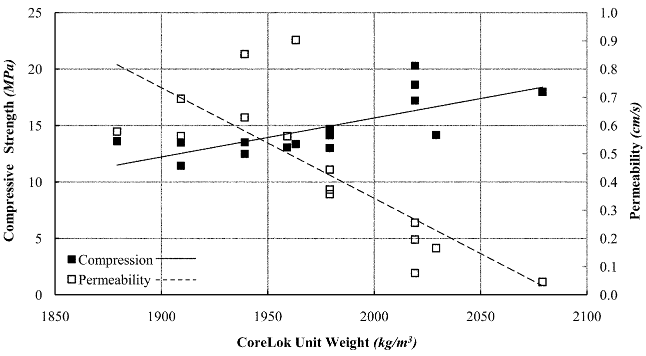

Fig. 10—Relationship between compressive strength, permeability, and unit weight. (Note: 1 MPa = 145.04 psi; 1 cm/s = 1417 in./h; and 1 kg/m³ = 0.0624 lb/ft³.)

The results also indicate that the NMAS of the aggregate gradation appears to have a more significant impact on permeability than either strength or effective porosity. The range in permeability values was much larger for the 12.5 mm (0.5 in.) mixtures compared to the 9.5 and 19.0 mm (0.38 and 0.75 in.) mixtures. This is likely due to the fact that the *w/c* was kept constant for all mixtures, thus creating excess paste in some cases (especially coarser mixtures) that would clog the voids in the concrete and reduce the permeability.

Determination of site-specific mixture gradations

The relationships between the primary properties of pervious concrete mixtures, compressive strength, permeability, and uniformity coefficient are illustrated in Fig. 9. The relationships between unit weight (determined by the CoreLok method) and compressive strength and permeability are presented in Fig. 10. The point at which the line of compressive strength intersects the line of permeability corresponds to a compressive strength of approximately 13.8 MPa (2000 psi) and a permeability of 0.55 cm/s (780 in./h) in both figures. These intersections occurred at a C_u of approximately 1.9 and a unit weight of approximately 1945 kg/m^3 (121.4 lb/ft^3). This point marks the region at which any further increase of compressive strength would adversely affect permeability if the conditions of this study were applied. The aggregate gradation that best fits the C_u and unit weight at the intersections was Mixture M. Mixture M had a C_u of 1.87, a unit weight of 1979 kg/m^3 (123.6 lb/ft^3), a compressive strength of 13.0 MPa (1886 psi), and a permeability of 0.44 cm/s (629 in./h). Because Mixture M consisted of a less uniform aggregate gradation with the *w/c* and *c/a* remaining constant with an NMAS of 19.0 mm (0.75 in.), the mixture had a tendency to be pasty. This being the likely case, Mixture M would have lower compressive strengths and permeability as compared to its optimal values. Figures similar to Fig. 9 and 10 have the potential for use as guides in predicting the best aggregate gradation for a pervious concrete mixture capable of having necessary permeability while maintaining adequate compressive strength.

CONCLUSIONS

Based on the results from this laboratory investigation on pervious concrete mixtures, the following conclusions were made:

- The compressive, split-tensile, and flexural strengths increased with the C_u to points, after which a decrease in strength was observed. This could indicate the presence of an optimum C_u for the strength of pervious concrete.

- The compressive, split-tensile, and flexural strengths are inversely related to permeability. As the permeability increased, the strength properties of pervious concrete mixtures decreased. It should also be noted that although permeability decreased significantly with increasing compressive strength, even some of the lower levels of permeability measured would be sufficient to allow storm water to infiltrate the pavement surface.
- The permeability and effective porosity decreased as the C_u increased to points, after which an increase was observed. This could indicate the presence of a pessimum C_u for permeability and porosity that corresponds to the optimum C_u for strength properties.
- The compressive, split-tensile, and flexural strengths of the single-sized aggregate gradations slightly decreased as the nominal maximum aggregate size increased, but these differences were not statically significant. The general trend of the blended aggregate gradations, however, did not follow consistent trends with respect to NMAS.

REFERENCES

ASTM C29/C29M-09, 2009, "Standard Test Method for Bulk Density "Unit Weight) and Voids in Aggregate," ASTM International, West Conshohocken, PA, 5 pp.

ASTM C33/C33M-08, 2008, "Standard Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 11 pp.

ASTM C39/C39M-09a, 2009, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA, 7 pp.

ASTM C78/C78M-10, 2010, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," ASTM International, West Conshohocken, PA, 4 pp.

ASTM C138/C138M-10a, 2010, "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete," ASTM International, West Conshohocken, PA, 4 pp.

ASTM C150/C150M-09, 2009, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 10 pp.

ASTM C192/C192M-07, 2007, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 8 pp.

ASTM C496/C496M-04, 2004, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA, 5 pp.

ASTM D448-08, 2008, "Standard Classification for Sizes of Aggregate for Road and Bridge Construction," ASTM International, West Conshohocken, PA, 3 pp.

ASTM D6752-09, 2009, "Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Automatic Vacuum Sealing Method," ASTM International, West Conshohocken, PA, 4 pp.

ASTM D7063, 2005, "Standard Test Method for Effective Porosity and Effective Air Voids of Compacted Bituminous Paving Mixture Samples," ASTM International, West Conshohocken, PA, 4 pp.

Bury, M. A.; Mawby, C. A.; and Fisher, D., 2006, "Making Pervious Concrete Placement Easy: Using a Novel Admixture System," *Concrete in Focus*, V. 5, No. 3, pp. 55-59.

Das, B. M., 2001, *Principles of Geotechnical Engineering*, fifth edition, Thomson Learning, 608 pp.

GDOT, 2003, "Georgia Department of Transportation's Progress in Open-Graded Friction Course Development," Georgia Department of Transportation, 9 pp.

Kevern, J.; Wang, K.; Suleiman, M. T.; and Schaefer, V. R., 2005, "Mix Design Development for Pervious Concrete in Cold Climates," *Proceedings of the 2005 Mid-Continent Transportation Research Symposium*, Iowa State University, Ames, IA, 67 pp.

Mindess, S.; Young, J. F.; and Darwin, D., 2002, *Concrete*, second edition, Prentice Hall, Upper Saddle River, NJ, 644 pp.

NRMCA, 2004, "Concrete in Practice: What, Why and How? CIP 38—Pervious Concrete," National Ready Mixed Concrete Association, Silver Spring, MD.

Schaefer, V. R.; Wang, K.; Suleiman, M. T.; and Kevern, J., 2006, "Mix Design Development for Pervious Concrete in Cold Climates," National Concrete Pavement Technology Center, Iowa State University, Ames, IA, 85 pp.

Tennis, P. D.; Leming, M. L.; and Akers, D. J., 2004, "Pervious Concrete Pavements," Portland Cement Association, Skokie, IL, and National Ready Mixed Concrete Association, Silver Spring, MD, 28 pp.

Yang, J., and Jiang, G., 2003, "Experimental Study on Properties of Pervious Concrete Pavement Materials," *Cement and Concrete Research*, V. 33, No. 3, pp. 381-386.