Pervious Concrete Mix Design for Wearing Course Applications

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ABSTRACT

Portland cement pervious concrete (PCPC) has shown great potential to reduce roadway noise, improve splash and spray, and to improve friction as a surface wearing course. This paper presents the results of studies conducted at Iowa State University and the National Concrete Pavement Technology Center (CP Tech Center) to develop mix designs and procedures for the use of PCPC overlays for highway applications. Issues related to characterization of workability, the need for air entrainment and the effect of air entrainment on durability, the development of design mixture proportions for mechanized placement, the evaluation of the curing requirements for surface abrasion resistance, and the development of overlay design procedures are presented and discussed. The results of these studies show that effective PCPC overlays can be designed for wearing course applications.

This presentation is part of the Sustainable Concrete Pavement Technologies session.

Key words: abrasion resistance—curing—overlay design—PCPC mix design—Portland Cement Pervious Concrete—workability
INTRODUCTION

Portland cement pervious concrete (PCPC) contains the same material components as conventional concrete of cementitious binder, aggregate, water, and chemical admixtures but through specific mixture proportioning, maintains around 20% porosity for water percolation. PCPC has shown great potential to reduce roadway noise, improve splash and spray, and to improve friction as a surface wearing course. A pervious concrete mix design for a surface wearing course must meet the criteria of adequate strength and durability under site-specific loading and environmental conditions. To date, two key issues that have impeded the use of pervious concrete in the United States are that strengths of pervious concrete have been lower than necessary for required applications and the freeze-thaw durability of pervious concrete has been suspect.

The strength and freeze-thaw durability of pervious concrete mix designs has been addressed in a recently completed study by Schaefer et al. (2006) who showed that a strong, durable pervious concrete mix design that will withstand hard, wet-freeze environments. The strength and durability is achieved through the use of a small amount of fine aggregate (i.e., concrete sand) and/or latex admixture to enhance the particle-to-particle bond in the mix. The preliminary results were reported in Kevern et al. (2005).

The National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is currently conducting a study entitled “An Integrated Study of Portland Cement Pervious Concrete for Wearing Course Applications.” The objective of the study is to conduct a comprehensive research program focused on the development of pervious concrete mix designs with adequate strength and durability for wearing course pavements. Mixtures are being designed to possess surface characteristics that reduce noise and enhance skid resistance while providing adequate removal of water from the pavement surface and structure. It is anticipated that, ultimately, a range of mix designs will be necessary to meet requirements for wearing course applications. Additionally, constructability issues for wearing course sections must be addressed to ensure that competitive and economical placement of the pervious concrete can be done in the field. Hence, during the evaluation phases, both laboratory and field testing of the materials and construction are being conducted, focusing on the development of a durable wearing course that can be used in highway applications for critical noise, splash/spray, skid resistance, and environmental concerns.

To maximize the potential benefits of pervious concrete as an overlay material for noise reduction and skid resistance, the mixture must possess the following properties:

- Adequate strength for long-term durability
- Highly durable aggregate
- Sufficient porosity (around 25%) to maximize noise reduction and minimize maintenance
- High workability for ease of placement and uniform porosity across the pavement thickness
- Ability to maintain voids when compaction is applied by the paver for uniform surface porosity

A number of tasks were developed to meet these objectives. This paper describes the results of research efforts to date, including (1) development of a method to characterize workability, (2) determination of the need for air entrainment and the effect of air entrainment on durability, (3) design mixture proportions for mechanized placement, (4) evaluation of the curing requirements for surface abrasion resistance, and (5) overlay design procedures and development. Work continues on other tasks of the project related to evaluation of the effect of deicing on pervious concrete durability, evaluation of clogging and permeability test development, and monitoring of field trials at the Minnesota Department of Transportation Cold Weather Road Research Facility (MnROAD), including measurement of road noise.
CHARACTERIZATION OF WORKABILITY

PCPC mixtures that have excellent performance in the lab may stiffen during transport, resulting in poor compaction or requiring additional water in the field. Addition of water at the jobsite increases water-to-cementitious binder ratio (w/c), impacting concrete strength and durability. Many practitioners of pervious concrete have experienced instances when principles applied from traditional concrete to pervious concrete have resulted in a less-than-optimal final product. To date, determining the workability of pervious concrete has been considered an art form since the conventional slump test does not provide useful information for such stiff concrete. The current method is to evaluate the concrete’s ability to form a ball with the plastic pervious concrete (Tennis et al. 2004). This method is impossible to specify due to lack of quantifiable values and individual bias. A more scientific method of workability determination is required if PCPC is to be used for large-scale parking areas and surface overlays.

Pervious concrete is designed to transport stormwater into the underlying layers through a series of interconnected voids, while providing the designed load-carrying capacity. The interconnected voids are produced from a balance between aggregate gradation and binder content. In the concrete mixture design, the objective is to provide a sufficient number of voids to infiltrate the design stormwater intensity. There is a direct relationship between voids and compressive strength, where lower void contents produce more intraparticle contact and consequently higher load-carrying capacities (Schaefer et al. 2006). The void content of the plastic and hardened pervious concrete can be determined from the unit weight. Determination of plastic workability becomes increasingly important since the required parameters (permeability and strength) are based on unit weight, which is achieved through proper placement. A highly workable mixture requires less compaction energy to achieve higher unit weight than a stiffer mixture. By quantifying pervious concrete workability, mixtures can be designed to produce certain void contents using specified compaction methods, and the workability can be verified and adjusted accordingly before placement.

A Superpave gyratory compactor (SGC) was modified to develop a test method to characterize the workability of pervious concrete. In this procedure, pervious concrete samples were produced using a SGC that allows for simulating various field compaction conditions. Workability of the concrete is then defined by the density versus gyration relationship. A matrix of concrete mixtures that consists of various w/c and cement contents were tested. The effect of mixing time on concrete workability is also evaluated so as to identify “slump loss” of field pervious concrete. The results show the SGC is able to produce consistent pervious concrete specimens, and the output of the test method well quantifies the workability and compactibility of the plastic concrete. The discussion includes a range of suggested values to allow design and verification of production pervious concrete workability.

It is well-understood that gyratory compactors better simulate the type of compaction utilized by the asphalt industry, primarily steel drum and pneumatic compaction (AI 2001). Since pervious concrete is loosely placed and then finished/compacted with either a weighted drum or roller-screed, the use of a gyratory compactor is appropriate to simulate field conditions. Normal conditions for Superpave asphalt design require a 600 kPa (87 psi) pressure for laboratory compaction to simulate field compaction (AI 2001). For this study, a gyratory compactor was modified to achieve compactive effort of 60 kPa (8.7 psi), within a tolerance of 2 kPa (0.3 psi), for 150 mm (6 in.) diameter samples.

A matrix of mixtures was tested across a variety of mixture properties, including cementitious material contents, w/c ratios, and duration of mixing times. Observation of the compaction curve defines both the initial concrete workability and the resistance of the mix to further compaction. A typical low-pressure compaction density relationship is shown in Figure 1. The Workability Energy Index (WEI) represents
the mixture’s initial workability, while the Compaction Densification Index (CDI) represents the resistance to additional compaction. Values are presented for acceptable ranges in Table 1.

![Figure 1. Compaction density and compactibility parameters for pervious concrete](image)

**Table 1. Ranges of pervious concrete workability values**

<table>
<thead>
<tr>
<th>Workability (WEI)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly Workable</td>
<td>&gt; 640</td>
</tr>
<tr>
<td>Acceptable Workability</td>
<td>640&gt;WEI&gt;600</td>
</tr>
<tr>
<td>Poor Workability</td>
<td>WEI&lt;600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compactibility (CDI)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-Consolidating</td>
<td>CDI&lt;50</td>
</tr>
<tr>
<td>Normal Compaction Effort Required</td>
<td>50&lt;CDI&lt;450</td>
</tr>
<tr>
<td>Considerable Additional Compaction Effort Required</td>
<td>CDI&gt;450</td>
</tr>
</tbody>
</table>

In pervious concrete, a larger amount of paste is exposed to the air than traditional concrete, making the fresh concrete especially susceptible to paste stiffening caused by loss of moisture and admixture effectiveness. A wide variety of materials are used to modify the workability and extend the placing window, and admixtures are used in pervious concrete without a method to quantify initial effects and effectiveness over time. Research was also performed to determine the effect of common admixtures, supplementary cementitious materials (SCMs), and physical modifiers on pervious concrete. The results show that admixtures have a shorter working window in pervious concrete. More detailed information on the workability of pervious concrete can be found in Kevern et al. (2009a).

**DETERMINING THE NEED FOR AIR ENTRAINMENT IN PERVIOUS CONCRETE**

The number of PCPC installations is increasing, especially in cold climates. It is widely accepted that air entrainment increases the freeze-thaw durability of traditional concrete (Kosmatka et al. 2002). The microscopic air-void system can provide spaces in the concrete to accommodate expansive materials, such as water that is expelled from ice formation, thus reducing hydraulic and osmotic pressures. PCPC has a more complicated void system than traditional concrete, containing not only the small-sized...
entrapped and entrained air in the paste or mortar but also porosity, the larger-sized interconnected void space between the paste-coated aggregate particles. While air content is a standard property of traditional concrete, no method is currently used to characterize the air voids in pervious concrete.

Due to the large porosity in pervious concrete, commonly used methods of concrete air measurement, such as pressure or volumetric air meters, do not provide useful data for pervious concrete, although the National Ready Mixed Concrete Association (NRMCA) suggests air-entraining pervious concrete at standard dosage rates to produce concrete curb mixtures (NRMCA 2005).

The RapidAir system is a relatively new device that automatically determines entrained air properties using ASTM C 457-98 (CEI 2002). Sample cross sections are stained black and then the voids are filled with a white material, such as zinc paste. The contrast allows the device to distinguish between air voids and the hardened matrix of either paste or aggregate. Recent studies have shown that the RapidAir system has a high degree of multi-lab reproducibility and has less variation than the manual technique (Jakobsen et al. 2006).

The air structure of pervious concrete was determined using the RapidAir system. The test results provide insight into whether or not the use of air-entraining agents (AEA) in pervious concrete is necessary and if the dosage rates of AEA used were sufficient to impact durability. Figure 2 shows wide and close-up views of samples prepared for RapidAir testing. Sample A has no air entrainment, while sample B has a double dosage of a synthetic air-entraining agent. The grey paste in sample B clearly distinguishes between aggregate, voids, and air-entrained paste. The results from freeze-thaw testing of mixtures with various levels of air entrainment are shown in Figure 3. The samples with no air entrainment (PG) had poor durability, while samples with air entrainment were much more durable. The best performing samples had a double dosage of a synthetic AEA.

From the study it was found that air entrainment increased the paste volume and improved workability of pervious concrete, thus reducing overall porosity and increasing density. The effect of air entrainment on porosity and workability is more pronounced for concrete made with the rounded pea gravel aggregate than for concrete made with the angular crushed limestone. Concrete having lower porosity and consequently higher unit weight displayed higher strength, better freeze-thaw resistance, and lower permeability. The RapidAir test results indicated that even without air entrainment, pervious concrete still had spacing factor values less than 0.2 mm (200 μm). This implies that it is the improved density resulting from air entrainment that enhanced freeze-thaw resistance. The recommended dosage of synthetic air entrainer produced equivalent contents of entrained air as the double recommended dosage of the natural air entrainer. Synthetic air entrainer produced higher amounts of air entrainment than the natural air entrainer at a given dosage. The entrained air-void structure of pervious concrete can be characterized using the RapidAir device. More information on the relationship between air entrainment and the freeze-thaw durability of pervious concrete can be found in Kevern et al. (2008a).

OPTIMIZATION OF PERVERIOUS CONCRETE MIXTURES FOR MECHANIZED PLACEMENT

As PCPC progresses from full-depth parking lot type applications to surface wearing course use in the United States, certain obstacles must be overcome to produce a durable surface. Pervious concrete used as a surface course will be subjected to much more extreme conditions, and the mix design must be optimized for strength, permeability, and especially better freeze-thaw durability. The objectives of the overlay mixture design are to produce a self-consolidating mixture that retains an interconnected void structure after mechanized placement. Mechanized placement will be required to produce a consistent surface texture (porosity in the top ½ in.) for uniform noise generation. A sufficient flexural strength will
be important for the ability to withstand traffic volumes higher than those experienced in parking lot applications. Sufficient bond strength will be required between the pervious overlay and the standard concrete to transfer loading without debonding.

Figure 2. RapidAir samples showing various levels of air entrainment

Figure 3. Freeze-thaw test results

The mixture design experimental phase was divided into eight sections determining aggregate type, binder-to-aggregate amount, optimized sand content, w/c ratio, fiber type, fiber addition rate,
cementitious material composition, and chemical admixture scheme. The objective was to produce a self-consolidating concrete that also required considerable additional compaction efforts, had porosity between 20% and 25%, and seven-day tensile strength greater than 2.1 MPa (305 psi). Typical pervious sections are opened to traffic after seven days, so mixtures were iterated on seven-day tensile strength and workability.

The selected coarse aggregate was crushed granite, with 98% passing the 9.5 mm sieve and 18% passing the 4.75 mm sieve, selected due to previous performance and availability. The granite had specific gravity of 2.65, absorption of 0.6%, micro-deval abrasion loss of 7%, and compacted voids of 45%.

Two types of fibers were used, a shorter fibrillated polypropylene previously investigated in pervious concrete and a cellulose micro-fiber (9). Fibers were included at 0.9, 1.8, and 3.0 kg/m³. Cementitious materials included Type II portland cement, class C fly ash, and grade 120 blast furnace slag investigated up to 50% replacement for cement with SCMs. The baseline mixture included a high-range water reducer and air-entraining agent; additional admixtures included individual viscosity modifiers and combinations of viscosity modifiers, hydration stabilizer, two latex-based workability aids, and slipform rheology modifying admixture.

Once the aggregate type and initial gradation were selected, the optimized binder content was investigated. Binder-to-aggregate (b/a) ratio was varied between 18% and 24% by volume. Mixture proportions were adjusted to maintain equal differential voltage contrast (DVC). A slight increase in initial workability occurred with increased binder, while a significant drop in required compaction energy occurred between 21% and 22.5%, with a small additional decrease at b/a = 24%. For all mixtures, porosity was between 25% and 30%, although seven-day compressive strength increased from 14.8 MPa (2150 psi) for b/a = 21% samples to 17.9 MPa (2600 psi) for b/a = 24% samples. At b/a greater than 24%, the samples were impermeable. In addition to the binder, w/c was varied for all three binder contents. Traditionally, water is added to pervious concrete to improve workability; at least for this combination of aggregate and binder volume, additional water did not improve workability. At w/c greater than 0.33, the paste drained from the aggregate creating the potential for imperviousness. A w/c of 0.29 was selected for subsequent iterations.

The effect of sand content on the original gradation was investigated for mixtures containing 21.5% binder and w/c of 0.29. Workability response for sand addition is shown in Figure 4 for 0% to 15% sand-to-gravel ratio (S/G) by mass. Initial workability increased slightly between 0% and 12.5%; however, between 7.5% and 10% there was a significant decrease in the required compaction energy. Sand increases the paste/mortar volume and the mortar viscosity, allowing the coarse aggregate particles to support a thicker paste layer. The increased paste viscosity did not significantly improve workability but separated the particles allowing better compaction. The mixture response is shown in Figure 5 for porosity and seven-day compressive strength. At S/G up to 10%, the fine aggregate bulks the mortar volume, creating better compaction and strength. Above S/G of 10%, the additional surface area demand of the fine aggregate begins to negatively impact the mixture properties.

For both types of fibers, there was no effect on initial workability with addition rate. Compactibility increased linearly with addition rate for the polypropylene fibers, while no increase in compactibility was observed until the 3 kg/m³ (5 pcy) rate for the cellulose fibers. A maximum seven-day tensile strength of 2.2 MPa (319 psi) occurred at the 3.0 kg/m³ (5 pcy) rate for the polypropylene fiber and of 2.0 MPa (290 psi) at the 0.9 kg/m³ (1.5 pcy) rate for the cellulose fibers. Cellulose fibers were selected due to the ability to maintain initial workability while requiring a higher level of compaction.
A range of SCM combinations were evaluated at 50% replacement for ordinary portland cement (OPC). The highest compressive and tensile strength occurred for samples containing 50% blast furnace slag. However, only a 0.10 MPa decrease in seven-day tensile strength occurred when the concrete contained 35% slag and 15% fly ash. Compressive strength was lower than 100% OPC for all SCM combinations, while all tensile strength results were higher. Due to the potential for greater long-term strength development, the (50% OPC, 35% slag, 15% fly ash) ternary mixture was selected. The highest workability occurred for the (50, 25, 25) and (50, 0, 50) mixtures, while the lowest required compaction energy was observed in the 50% fly ash (50, 0, 50) mixture. All combinations of SCMs had higher workability and lower required compaction energy than the OPC mixture.

All combinations of chemical admixtures improved the initial workability and most decreased the required compaction energy. The selected non-polymer mixture contained a viscosity-modifying agent (VMA) and hydration stabilizer (HS), which did not affect the WEI but caused a drop in CDI. To potentially increase bond strength during subsequent testing, a polymer-modified mixture was also selected. Testing was performed in the saturated state without drying to coalesce the polymer film, which is expected to further increase tensile strength. The latex admixture caused a slight drop in WEI but a substantial increase in CDI. Future testing may include workability behavior with more realistic increased mixing times and drying cycles to mimic field conditions. Additional information on the overlay mixture proportions can be found in Kevern et al. (2008b).

CURING AND SURFACE ABRASION RESISTANCE TESTING

When pervious concrete is applied to pavements in areas that undergo freeze-thaw, durability also refers to the surface abrasion resistance against snow-clearing operations. If pervious concrete is to progress from parking lot applications to low-volume and potentially high-volume applications, the pavement must be resistant to all aspects of cold weather maintenance.

Concrete curing is required to maintain sufficient moisture to allow cement hydration and concrete microstructure development (Wang et al. 2006). Also, curing has been shown to impact concrete durability as well as concrete strength (ACI 2000). Many techniques exist to control moisture loss in traditional concrete, although most are not appropriate for pervious concrete. Because of the high porosity of pervious concrete, rapid loss of moisture from the fresh concrete due to evaporation can occur. Since the w/c of the concrete is generally low, loss of moisture can result in rapid desiccation, low strength, and excessive surface raveling. Thus, curing is especially important for pervious concrete, because unlike...
traditional concrete, the bottom of the slab is exposed to air as much as the surface. On the other hand, protecting the surface may allow proper curing throughout. For PCPC, water misting or fogging washes the cement paste from the coated aggregate particles. Due to potential surface damage of the fresh concrete, wet burlap cannot be applied until final set has been reached, which results in excess surface desiccation. Liquid membrane-forming compounds prevent surface moisture loss but do nothing to prevent evaporation from within pervious concrete. Curing compounds are designed to prevent moisture loss from the surface of freshly placed concrete, which presents an obstacle for proper pervious concrete curing.

The current method of curing PCPC involves covering the fresh concrete with plastic sheets and allowing the pavement to cure for seven days before removal of the plastic. In most cases, the plastic sheets must be rolled onto a pipe for rapid application after placement, and aggregate or sand bags must be used to seal the edges and prevent wind from ballooning under the plastic and drying the surface. Covering with plastic is the preferred method to cure pervious concrete but can be problematic and no studies have been performed to determine if covering is sufficient or even required. Pervious concrete samples were evaluated for nine different curing methods or curing materials by flexural strength and surface abrasion resistance.

Flexural strength was determined using modulus of rupture of the beams tested at 28 days according to ASTM C 78. Once the samples were tested for modulus of rupture, the fractured pieces were tested for surface abrasion. Surface abrasion was determined according to ASTM C 944, in which a constant load of 98 N (22 lbs) is applied through rotary cutter dressing wheels in contact with the sample surface for two minutes. The diameter of the circular abraded area is 80 mm (3.25 in.). The beams were first cleaned with a stiff-bristled brush and vacuumed on all sides to remove any loose materials. After each abrasion test, the beams were again brushed clean and vacuumed to remove loose debris. The mass loss between trials was recorded and a total of six abrasion tests were performed on each set of beams. Figure 6 shows the abrasion device with the shaft-mounted container for load calibration and abrasion head-cutting device. The physical result of an abrasion test is shown in Figure 7 for a beam cured with the standard white-pigment curing compound. The left portion of the sample had not undergone testing while the tested portion is the exposed aggregate circular section on the right. The Abrasion Index (AI) was taken as the ratio of the average abraded mass loss for a particular sample divided by the average for the control mixture with no curing method.

![Figure 6. Surface abrasion device](image1)

![Figure 7. Abrasion physical test results](image2)
Results show that the samples cured under plastic had the best abrasion resistance and highest flexural strength. There was no significant difference in flexural strength between samples cured under plastic for 7 or 28 days, although abrasion resistance did increase with the duration of curing. Soybean oil has the potential to be used as an effective curing compound. In this study, the soybean oil emulsion produced the best surface durability and increase in flexural strength of the surface-applied curing agents. The “birds nest effect” caused by the fibers increased the porosity by 7.9% and yet produced a flexural increase of 21% over the control, without significantly impacting surface abrasion. The rotary-cutter surface abrasion ASTM C 944 method has the ability to differentiate between curing methods, allowing relative surface durability comparisons. More information on curing and abrasion of pervious concrete can be found in Kevern et al. (2009b).

OVERLAY DESIGN PROCEDURES AND DEVELOPMENT

One important aspect of a bonded overlay is the bond strength between the substrate and the overlay. Pervious concretes have been placed wet-on-wet, which produces very high bond strength. However, traditional pervious concrete does not lend itself to high bond strength over existing pavement due to the dry nature of the mixture and the reduced contact area. Fortunately, pavement modeling of pervious concrete wearing course indicates a relatively low strength is required of 145 psi (Bax et al. 2007).

Simulated overlay mixtures have been placed with the two selected pervious concrete mixtures over standard concrete: one containing the VMA and the other the latex additive. Samples were placed without any compaction or vibration to textureless prepared concrete specimens. Various bonding methods included a clean and dry surface, poly-modified grout, standard grout, and a polymer tack coat. Samples were tested using the shear device shown in Figure 9 and the Iowa Department of Transportation (Iowa DOT) test method 406 C, which applies load at 400–500 psi/min. The absence of vibration or compaction was designed to produce the lowest and most conservative bond values possible for these particular mixtures and techniques. It has been observed that the normal amount of vibration present during placement will tend to draw some pervious paste to the bond interface and is expected to greatly improve strength. Samples have been placed at less conservative, more realistic vibration levels to determine the effect on bond strength.

Results from the overlay shear testing indicate variability was high with bond strength either good or poor; one example includes a clean, dry polymer mixture with variability from 22 psi to 215 psi. The average for the clean and dry polymer concrete samples was below the limit at 111 psi, although some samples were well above the required value. Additional research is needed to determine a realistic
placement technique to reduce the testing variability and determine the actual required pavement conditions.

![Testing shear strength of overlay bond](image)

**Figure 9. Testing shear strength of overlay bond**

**SUMMARY**

PCPC has shown great potential to reduce roadway noise, improve splash and spray, and to improve friction as a surface-wearing course. This paper has presented the results of studies conducted to develop a method to characterize workability, determine the need for air entrainment and the effect of air entrainment on durability, develop design mixture proportions for mechanized placement, evaluate the curing requirements for surface abrasion resistance, and develop overlay design procedures. The results of these studies show that effective PCPC overlays can be designed for wearing course applications.
ACKNOWLEDGMENTS

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