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Mixture Proportion Development and Performance Evaluation of Pervious Concrete for Overlay Applications

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This paper describes the results of studies to develop pervious concrete for use as an overlay material over traditional concrete to reduce noise, minimize splash and spray, and improve friction as a surface wearing course. Workability and compaction density testing methods were developed to ensure constructibility and placement consistency. The mixture testing matrix consisted of evaluating aggregate type and gradation, cementitious material amounts and composition, and various admixtures. Selected mixtures were tested for permeability, strength, workability, overlay bond strength, and freezing-and-thawing durability. The selected mixture was self-consolidating and slip-formable and was placed at the MnROAD testing facility during late October 2008. The test results indicate that pervious concrete mixtures can be designed to be highly workable, sufficiently strong, permeable, and have excellent freezing-and-thawing durability, thus being suitable for pavement overlays.

Keywords: concrete overlay; durability; freezing and thawing; pervious concrete; storm-water management; sustainability.

INTRODUCTION

Portland cement pervious concrete (PCPC) is increasingly used in construction due to its many environmental benefits. In the U.S., PCPC is generally used in parking areas, residential roads, alleys, and driveways for storm-water management. In Europe, Japan, and Australia, PCPC has also been successfully employed in limited highway applications. PCPC has provided quieter and safer pavements by reducing traffic noise and water splash and spray and increasing skid resistance.[1-4]

One concern about the expanded use of PCPC as a structural material is its relatively low strength caused by high porosity required for high permeability. To minimize this deficiency and maximize environmental benefits, using PCPC as a pavement overlay material is a rational approach. Pavement overlaid with pervious concrete will not only function well structurally for carrying designed traffic loads, but also perform well environmentally for noise reduction and skid resistance.

To ensure good performance during both the construction and service periods, a PCPC mixture for a pavement overlay must possess the following properties:

- High workability for ease of placement;
- Uniform porosity or void structure throughout the pavement for noise reduction;
- Adequate bond with underlying pavement and proper strength for traffic load; and
- Sufficient resistance to wearing, aggregate polishing, and freezing-and-thawing damage.

While a PCPC overlaid on existing concrete had previously never been attempted, a mixture with good durability and bond to the subsequent surface should have similar performance to traditional concrete overlays. This paper details the mixture proportion development and performance evaluations for the first pervious concrete overlay project in the U.S. The evaluated mixture performance parameters included concrete workability, compaction density, strength, freezing-and-thawing durability, and overlay bond strength.

RESEARCH SIGNIFICANCE

The first pervious concrete overlay project in the U.S. is presented in this paper. In this project, a systematic study was conducted to investigate the effects of a wide variety of concrete materials and mixture proportions on PCPC performance (such as workability, strength, and durability). The results indicate that PCPC mixtures can be designed to be highly workable, sufficiently strong, permeable, and have excellent freezing-and-thawing durability. Such PCPC mixtures are suitable for pavement overlays. The pavement with a PCPC overlay will not only function well structurally for carrying designed traffic loads, but also perform well environmentally for noise reduction and skid resistance. A field test has indicated that the placed PCPC overlay is the quietest concrete pavement tested in the U.S. under the FHWA surface characteristics track of the CP Roadmap. The project has clearly demonstrated a high potential for extending the application of PCPC to pavement overlays.

PROJECT BACKGROUND AND SITE INFORMATION

The MnROAD is a cold weather testing facility located on Interstate 94 (I-94), north of Minneapolis and St. Paul, MN. The facility contains two primary test sections: mainline and low-volume loop. The mainline is a 5.6 km (3.5 mile) section parallel to I-94 with the capability to divert traffic from I-94 to the mainline section. The low-volume section is a closed 4 km (2.5 mile) loop. The pavement on the low-volume loop contains two lanes—one tested with a 36,300 kg (80 kip) controlled five-axle truck, and the second an environmental lane with no traffic loading. The low-volume loop contains 24 approximately 150 m (500 ft) long test cells containing different pavement types, thicknesses, and subbase/subgrade structures. The PCPC overlay was placed on a test cell of the low-volume loop. The overlay test section consists of concrete pavement that is nominally 165 mm (6.5 in.) thick with transverse tining, skewed joints, and 6 x 3.7 m (20 x 12 ft) panels. Load transfer is achieved with 25 mm (1 in.) dowels. The PCPC overlay is 100 mm (4 in.) thick with formed joints approximately over the original skewed joints.

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Table 1—Mixture matrix summary

Evaluated parameters	Tested values and components
Aggregate shape	Round, angular
Sand content, FA/CA	0, 7.5, 10, 12.5, 15%
Cementitious content, B/A	10, 15, 20, 22.5, 24, 25
SCMs	Fly ash, slag
w/c	0.27, 0.29, 0.31, 0.33
Fiber type/length	PS, PL, CS
Fiber dosage, kg/m^3	0, 0.9, 1.8, 3.0
Admixtures	HRWRA, AEA, HS, LX, and VMA

Note: 1 kg/m^3 = 1.69 lb/yd^3.

The jointing pattern represents much larger spacing than is recommended for traditional concrete overlays. Because the level of bonding expected in the field was low, the large panels represented a worst-case scenario for curling and warping stresses.

CONCRETE MATERIALS AND MIXTURE PROPORTIONS

Table 1 summarizes the material and mixture proportion parameters studied for this project. Many of the variables and starting mixture proportions were based on previous work.[5-9]

Previous studies have suggested that concrete made with angular aggregate generally requires more paste to produce a given workability than pervious concrete made with like-sized rounded aggregate.[5,8,10] For a given aggregate type, PCPC made with angular aggregate commonly has higher tensile strength than concrete produced with rounded aggregate when comparing two PCPCs with similar densities and void contents. Angular/crushed aggregate also has better paste-aggregate bonding and generally provides pervious concrete with better freezing-and-thawing durability than most rounded aggregates.[5] Therefore, locally available crushed granite was selected as the coarse aggregate (CA) for the PCPC in this study. The CA had 18% (by weight) passing the 4.75 mm (No. 4) sieve, a specific gravity of 2.65, an absorption of 0.59%, and compacted voids of 45%. In addition to the sand-sized particles present in the CA, 10% river sand was used as the fine aggregate (FA). As a result, the combined aggregate gradation in the studied PCPC contained approximately 30% FA. Because both the CA and FA had similar specific gravities, the FA/CA ratios expressed by mass and volume in the PCPC proportions were similar.

The total cementitious content was varied to achieve the proper paste thickness surrounding the aggregate for workability, strength, and durability.[11] The initial paste content of 24% by weight of aggregate was selected to achieve the proper paste thickness for the desired workability on the relatively finely graded angular CA.[10] With the selected aggregate gradation, two additional cementitious contents were evaluated. Supplementary cementitious materials (SCMs) were investigated in both binary and ternary combinations up to a 50% replacement for portland cement. A 50% SCM replacement for cement has become common in some state Departments of Transportation (DOTs) and often results in improved properties compared to straight cement mixtures.[12]

The water-cementitious material ratio (*w/cm*) was varied across typical values for PCPC. Various fiber lengths and types were investigated at three addition rates up to 3.0 kg/m^3 (5.0 lb/yd^3) of concrete. Two lengths of fibrillated polypropylene fibers were investigated: a longer fiber (PL) with a length of 50 mm (2 in.) and a shorter fiber (PS) with a gradation of lengths ranging from 12 to 25 mm (0.5 to 1 in.). Cellulose microfibers (CS) were also investigated with a maximum length of 2 mm (0.1 in.). Both the polypropylene fibers had a denier of 360 and 2.5 to 3.0 for the cellulose fiber. Various combinations of fibers were also studied. The use of fibers in pervious concrete for improved freezing-and-thawing durability and permeability was first presented by Kevern et al.[6]

Fibers were also used as workability modifiers in this study. Admixtures were investigated individually and in combinations at typical and increased dosage rates. The standard baseline mixture contained a polycarboxylate high-range water-reducing admixture (HRWRA) and a vinsol resin air-entraining agent (AEA), which is typical for laboratory pervious concrete.[5-7] The dosages were 0.25% and 0.13%, respectively, from previous testing.[5] Additional admixtures included a hydration-stabilizing (HS) admixture, a polysaccharide viscosity-modifying admixture (VMA), and a 2% solids triethanolamine latex polymer additive (LX), successfully used in pervious concrete by the Australian transportation ministry.[2] Because traditional concrete overlays have been successful with and without bonding agents, two versions of the selected mixture proportions were studied: one with an LX and one without.

Taking into consideration all the aforementioned variables, a variety of PCPC proportions were selected, as shown in Table 2(a) for the basic mixtures and Table 2(b) for the more advanced mixtures. All the mixtures were designed to yield 17.5% voids. The mixtures' iterations were based on workability, 7-day compressive strength, and 7-day splitting tensile strength using a partial factorial offspring progression where the next set of variables is applied to the selected mixture from the previous set of tests. The selected mixture represents the best performance (workability and strength) from the progeny and then becomes the baseline mixture for the next set of variables. The breeding process continues through the testing matrix and the final mixture represents a genetic offspring of the previous test variables as selected by progressive traits. After the final mixture proportions were selected, compaction density curves were developed and calibrated to the placing equipment following the procedure developed by Kevern et al.[13]

TESTING PROCEDURES

The following are testing procedures unique for the development of the pervious concrete overlay. Workability and compaction density procedures were developed specifically for this project and have been applied to many subsequent designs.[10,14]

Table 2(a)—PCPC mixture proportions for variables related to basic concrete materials

Mixture design variables	Mixture ID	Cement, kg/m^3 (lb/yd^3)	Slag, kg/m^3 (lb/yd^3)	Fly ash, kg/m^3 (lb/yd^3)	Water, kg/m^3 (lb/yd^3)	CA, kg/m^3 (lb/yd^3)	FA, kg/m^3 (lb/yd^3)
Sand	B24	380 (640)	0 (0)	0 (0)	110 (190)	1571 (2650)	0 (0)
	B24-S7.5	380 (640)	0 (0)	0 (0)	110 (190)	1480 (2490)	110 (190)
	B24-S10	380 (640)	0 (0)	0 (0)	110 (190)	1440 (2430)	140 (240)
	B24-S12.5	380 (640)	0 (0)	0 (0)	110 (190)	1410 (2380)	180 (300)
	B24-S15	380 (640)	0 (0)	0 (0)	110 (190)	1380 (2320)	210 (350)
Binder amount	B21-S10	350 (580)	0 (0)	0 (0)	100 (170)	1500 (2520)	150 (250)
	B22.5-S10	360 (610)	0 (0)	0 (0)	100 (170)	1470 (2480)	150 (250)
	B24-S10	380 (640)	0 (0)	0 (0)	110 (190)	1440 (2430)	140 (240)
	B21-S10 (0.33)	340 (570)	0 (0)	0 (0)	110 (190)	1470 (2480)	150 (250)
	B22.5-S10 (0.33)	360 (600)	0 (0)	0 (0)	120 (200)	1440 (2430)	140 (240)
	B24-S10 (0.33)	370 (630)	0 (0)	0 (0)	110 (180)	1420 (2390)	140 (240)
w/c	B24-S10 (0.27)	380 (650)	0 (0)	0 (0)	100 (170)	1460 (2430)	150 (250)
	B24-S10 (0.29)	380 (640)	0 (0)	0 (0)	110 (190)	1440 (2430)	140 (240)
	B24-S10 (0.33)	370 (630)	0 (0)	0 (0)	110 (180)	1420 (2390)	140 (240)

Table 2(b)—PCPC mixture proportions for variables related to fibers and admixtures

Mixture design variables	Mixture ID	PL, kg/m^3 (lb/yd^3)	PS, kg/m^3 (lb/yd^3)	CS, kg/m^3 (lb/yd^3)	VMA, mL/kg (oz/cwt)	HS, mL/kg (oz/cwt)	LX, mL/kg (oz/cwt)
Fiber type	B24-S10-PL1.5	0.9 (1.5)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	B24-S10-PS1.5	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)	0 (0)
	B24-PS1.5	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)	0 (0)
	B24-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
Fiber dosage rate	B24-S10-PS1.5	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)	0 (0)
	B24-S10-PS3	0 (0)	1.8 (3.0)	0 (0)	0 (0)	0 (0)	0 (0)
	B24-S10-PS5	0 (0)	2.7 (5.0)	0 (0)	0 (0)	0 (0)	0 (0)
	B24-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
	B24-S10-PS1.5-CS1.5	0 (0)	0.9 (1.5)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
Binder composition	B24(100,0,0)-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
	B24(50,35,15)-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
	B24(50,25,25)-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
	B24(50,15,35)-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
	B24(50,50,0)-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
	B24(50,0,50)-S10-CS1.5	0 (0)	0 (0)	0.9 (1.5)	0 (0)	0 (0)	0 (0)
Admixtures	B24(50,35,15)-S10-CS1.5-VMA5	0 (0)	0 (0)	0.9 (1.5)	3 (5)	0 (0)	0 (0)
	B24(50,35,15)-S10-CS1.5-HS6	0 (0)	0 (0)	0.9 (1.5)	0 (0)	4 (6)	0 (0)
	B24(50,35,15)-S10-CS1.5-HS12	0 (0)	0 (0)	0.9 (1.5)	0 (0)	8 (12)	0 (0)
	B24(50,35,15)-S10-CS1.5-VMA5-HS12	0 (0)	0 (0)	0.9 (1.5)	3 (5)	0 (0)	8 (12)
	B24(50,35,15)-S10-CS1.5-LX12	0 (0)	0 (0)	0.9 (1.5)	0 (0)	8 (12)	0 (0)
Selected mixtures	B24(50,35,15)-S10-CS1.5-VMA5-HS12	0 (0)	0 (0)	0.9 (1.5)	3 (5)	8 (12)	8 (12)
	B24(50,35,15)-S10-CS1.5-LX12-HS12	0 (0)	0 (0)	0.9 (1.5)	0 (0)	8 (12)	8 (12)

Workability

Pervious concrete mixtures with excellent performance in the lab may stiffen during transport, resulting in poor compaction or requiring additional water in the field. The addition of water at the job site increases the *w/cm*, impacting concrete strength and durability. To date, determining the workability of pervious concrete has been considered an art form because the conventional slump test does not provide useful information for stiff concrete. The current method is to evaluate the ability to form a ball with the plastic pervious concrete.[15] This method is impossible to specify due to the lack of quantifiable values and individual bias. A more scientific method of workability determination was required to develop the surface overlays.

The water-permeable voids are produced from a balance between aggregate gradation and binder content. There is a direct relationship between voids and compressive strength, where lower void contents produce more interparticle contact and consequently higher load-carrying capacities.[16] The determination of plastic workability becomes increasingly important because 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 a 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

Table 3—Ranges of pervious concrete workability value[11]

Workability (WEI)	
Behavior	**Range**
Highly workable	WEI > 640
Acceptable workability	640 > WEI > 600
Poor workability	WEI < 600
Compactability (CDI)	
Explanation	**Range**
Self-consolidating	CDI < 50
Normal compaction effort required	50 < CDI < 450
Considerable additional compaction effort required	CDI > 450

pervious concrete simulating various field compaction conditions. By analyzing the initial compaction behavior with the resistance provided through aggregate friction, both important behaviors were defined.[10] In Table 3, values are presented for acceptable ranges. The workability energy index (WEI) is defined by the immediate, rapid reduction in voids that occurs upon initial compaction. WEI indicates the relative workability of the pervious concrete mixture, with a high value representing a more fluid mixture. The compaction density index (CDI) is defined by the rate of compaction beyond the initial rapid phase. A high CDI represents high internal friction and resistance to void reduction upon additional compaction.

In addition to measuring workability, samples were extruded to indicate edge-holding ability through the slip-forming process. Mixtures were defined as either extrudable with shape-holding ability or not extrudable and collapsing upon discharge from the mold. The new test method is able to distinguish the changes in mixture workability from a variety of factors, including aggregate gradation, binder volume and composition, fibers, admixtures, and working time.

Strength and durability

Compressive strength was tested on 100 x 200 mm (4 x 8 in.) sulfur-capped cylinders according to ASTM C39 and C617.[17,18] The splitting tensile strength was tested on 100 mm (4 in.) diameter specimens according to ASTM C496.[19] Freezing-and-thawing durability was tested according to the ASTM C666 (A) fully saturated rapid technique using a 60% relative dynamic modulus of elasticity (RDM) criterion according to ASTM C215.[20,21] Surface abrasion was measured using the ASTM C944[22] rotary cutter method on samples before and after freezing-and-thawing testing.

Sample placement and compaction density

The results shown in Tables 4 and 5 and Fig. 1 through 5 are from samples placed by a single experienced operator. Concrete cylinders were placed in three lifts, lightly rodding each lift with 25 strokes. All data represent an average of three test specimens with a coefficient of variation (COV) of less than 15%. The freezing-and-thawing durability specimens were placed at exactly the design void content by placing a predetermined mass into the known sample mold volume. Compaction was achieved by lightly rodding the concrete in two lifts.

The creation of compaction density curves is necessary to evaluate pervious concrete material properties over a range of void contents. Because a particular mixture can result in a wide range of material properties related to density, compaction density curves are needed to encompass potential installed values. Cylinder samples and modulus of rupture beams of selected mixtures were placed at three different densities to encompass the desired field density. The cylinders were then tested for unit weight, voids, permeability, and strength development with time. Voids were determined using water displacement and the procedure outlined by Montes et al.[23] The resulting compaction density relationships allow for the specification of design void content with individual compaction equipment and the verification of delivered fresh concrete properties. Additional information on the creation of compaction density relationships for pervious concrete is provided by Kevern et al.[13] and Kevern and Montgomery.[14]

Overlay bond strength

Overlay bond strength was tested according to Iowa DOT test method 406C.[24] This test standard calls for applying a constant load at 2.8 to 3.4 MPa/min (400 to 500 psi/min) to a 100 mm (4 in.) diameter specimen. Traditional concrete samples were placed at a height of approximately 100 mm (4 in.). After curing for 28 days, an additional 100 mm (4 in.) of pervious concrete was placed on the hardened concrete. The surface of the PCPC was leveled using a flat plate without applying any pressure. The reported bond strength is the maximum achieved. The overlay bond strength testing is shown in Fig. 6.

RESULTS AND DISCUSSIONS

Table 4 shows the voids, unit weight, and workability parameters (CDI and WEI) of fresh PCPC, as well as the 7-day compressive strength of the hardened PCPC studied for all mixtures in the progression toward the selected mixtures shown in Table 4. The mixture iterations were based on 7-day strengths due to the opening criteria of the pervious concrete being cured for 7 days before the removal of the plastic. The effects of the concrete material and mixture proportion variables on the PCPC properties are discussed in the sections that follow.

Workability and strength performance

Figure 1 illustrates the effect of binder content on the concrete's workability, strength, and porosity. The selected baseline mixture contained 10% FA to CA and cement and had a *w/c* of 0.29. The range of binder-aggregate (B/A) combinations selected represented common cement contents for aggregates with similar surface area values that had produced successful placements in the past. It has been observed that B/A values of less than 21% (by mass of straight cement using aggregates with specific gravity values of approximately 2.62) had high porosity but low strength. It was also observed that B/A above 24% had good strength but low permeability.[5,7] At increasing B/A, the initial workability (WEI) slightly increased, whereas the resistance to compaction (CDI) significantly decreased. Porosity was not impacted by the additional binder, although more binder did improve strength. The B/A of 24% was selected due to its highest strength and workability and its lowest resistance to additional compaction.

The effect of *w/c* on workability and material properties is shown in Fig. 2 for mixtures containing a B/A of 24%, 10% additional FA, and cement. Previous research has shown that at a *w/c* less than 0.27 typical pervious concrete (standard admixture types and dosages), the paste is not sufficiently

Table 4—PCPC test results

Mixture design variables	Mixture ID	Voids, %	Unit weight, kg/m^3 (lb/ft^3)	7-day compressive strength, MPa (psi)	CDI	WEI
Sand	B24	32.5	1770 (111)	12.3 (1780)	592	650
	B24-S7.5	31.1	1850 (116)	19.2 (2790)	613	625
	B24-S10	28.7	1850 (116)	17.9 (2600)	630	187
	B24-S12.5	22.7	1950 (122)	11.4 (1660)	636	112
	B24-S15	31.4	1820 (114)	9.8 (1420)	625	99
Binder amount	B21-S10	29.3	1860 (116)	14.8 (2140)	611	663
	B22.5-S10	28.1	1890 (118)	15.5 (2250)	624	266
	B24-S10	28.7	1850 (116)	17.9 (2600)	630	187
	B21-S10 (0.33)	28.4	1830 (114)	11.2 (1630)	609	662
	B22.5-S10 (0.33)	20.3	1910 (119)	13.3 (1920)	621	517
	B24-S10 (0.33)	13.0	1960 (122)	13.5 (1970)	628	193
w/*c*	B24-S10 (0.27)	32.6	1820 (114)	12.1 (1750)	618	244
	B24-S10 (0.29)	28.7	1850 (116)	17.9 (2600)	630	187
	B24-S10 (0.33)	13.0	1960 (122)	13.5 (1970)	628	193
Fiber type	B24-S10-PL1.5	24.1	1920 (120)	14.4 (2100)	619	389
	B24-S10-PS1.5	18.4	1970 (123)	19.5 (2830)	621	380
	B24-PS1.5	27.9	1860 (116)	16.1 (2340)	650	48
	B24-S10-CS1.5	26.2	1940 (121)	20.6 (2990)	626	251
Fiber dosage rate	B24-S10-PS1.5	18.4	1970 (123)	19.5 (2830)	621	380
	B24-S10-PS3	24.9	1940 (121)	19.2 (2790)	617	431
	B24-S10-PS5	26.8	1900 (118)	14.6 (2120)	607	666
	B24-S10-CS1.5	26.2	1940 (121)	20.6 (2990)	626	251
	B24-S10-PS1.5-CS1.5	28.8	1880 (117)	16.2 (2346)	621	310
Binder composition	B24(100,0,0)-S10-CS1.5	26.2	1940 (121)	20.6 (2990)	626	251
	B24(50,35,15)-S10-CS1.5	22.7	1980 (123)	17.6 (2560)	638	113
	B24(50,25,25)-S10-CS1.5	19.5	1990 (124)	16.8 (2440)	644	103
	B24(50,15,35)-S10-CS1.5	21.5	1970 (123)	14.9 (2160)	635	115
	B24(50,50,0)-S10-CS1.5	19.8	2010 (125)	23.7 (3437)	636	84
	B24(50,0,50)-S10-CS1.5	23.8	1910 (119)	14.3 (2070)	641	86
Admixtures	B24(50,35,15)-S10-CS1.5-VMA5	20.5	1930 (120)	12.5 (1810)	637	110
	B24(50,35,15)-S10-CS1.5-HS6	21.3	1960 (123)	17.6 (2560)	635	139
	B24(50,35,15)-S10-CS1.5-HS12	24.7	1950 (122)	19.8 (2870)	642	82
	B24(50,35,15)-S10-CS1.5-VMA5-HS12	20.9	1980 (124)	20.3 (2940)	689	0
	B24(50,35,15)-S10-CS1.5-LX12	25.1	1910 (119)	15.1 (2190)	617	634

wetted and has poor strength and durability. Again, for typical pervious concrete mixtures, a *w*/*c* above 0.33 causes the excess paste to drain from the aggregate.[11,25] Consequently, a range of *w*/*c* from 0.27 to 0.33 was studied for overlay applications. Additional water slightly improved workability and caused a significant reduction in porosity at a *w*/*c* of 0.33; however, strength was highest (17.9 MPa [2600 psi]) at the selected *w*/*c* of 0.29.

The effect of gradation/sand content is shown in Fig. 3 for mixtures containing a B/A of 24% and a *w*/*c* of 0.29. Because the original CA gradation had 18% passing the 4.75 mm (No. 4) sieve, a maximum of 15% additional FA was investigated. The FA had similar specific gravity to the CA, so the FA/CA is either by mass or volume. Workability (WEI) increased with increased sand content. At an FA/CA less than 7.5%, there was no difference in resistance to compaction; however, with an FA/CA greater than 7.5%, the FA increased the paste/mortar thickness around the aggregate and reduced resistance to further compaction. The porosity decreased with increased workability up to an FA/CA of 12.5%. At 15%, the amount of sand stiffened the mortar and held the CA particles apart. Whereas the porosity decreased to 12.5%, the 7-day compressive strength peaked at 7.5% at 19.2 MPa (2793 psi). Due to the decrease in resistance to compaction between 7.5 and 10% and only a slight decrease in compressive strength, an FA/CA of 10% was selected for this application.

Table 5—Selected mixtures and their test results

Mixture ID	B24(50,35,15)-S10-CS1.5-PS1.5-VMA5-HS12	B24(50,35,15)-S10-CS1.5-PS1.5-LX12-HS12
Voids, %	17.2	23.0
Unit weight, kg/m^3 (lb/ft^3)	1950 (122)	1950 (122)
7-day compressive strength, MPa (psi)	17.2 (2500)	15.9 (2300)
21-day compressive strength, MPa (psi)	19.7 (2860)	22.8 (3310)
28-day compressive strength, MPa (psi)	21.2 (3070)	23.2 (3360)
28-day splitting tensile strength, MPa (psi)	2.70 (395)	2.80 (410)
Permeability, cm/s (in./h)	0.12 (170)	0.21 (300)
WEI	689	692
CDI	0	0

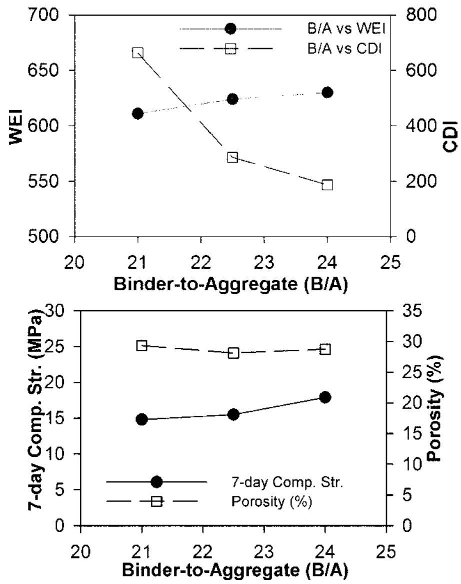

Fig. 1—B/A versus workability, strength, and porosity. (Note: 1 MPa = 145 psi.)

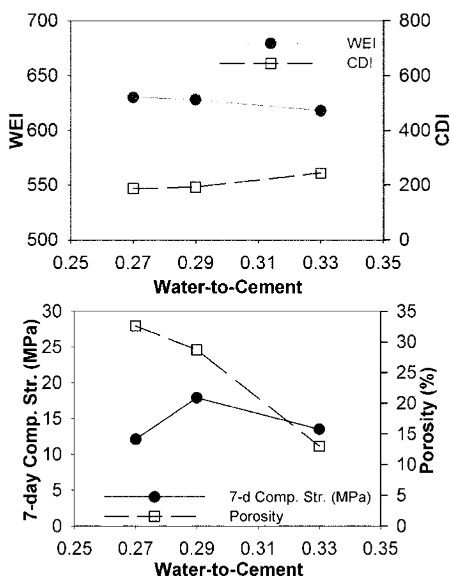

Fig. 2—Effect of w/c *on workability, strength, and porosity. (Note: 1 MPa = 145 psi.)*

The effects of different types of fibers on the workability of a mixture containing a B/A of 24%, a *w/c* of 0.29, and an FA/CA of 10% are shown in Fig. 7 for both the PS and CS fibers. The general trends were the same for both fiber types. Additional fibers slightly decreased workability and increased the resistance to additional compaction. Mixtures containing polypropylene fibers had a linear increase in resistance to additional compaction, whereas no significant increase was observed for the CS fibers until 3.0 kg/m^3 (5.0 lb/yd^3). All mixtures had similar increases in tensile and compressive strengths at 0.9 and 1.8 kg/m^3 (1.5 and 3.0 lb/yd^3) and a decrease in compressive strength at 3.0 kg/m^3 (5.0 lb/yd^3). One interesting observation was noted: mixtures containing the polypropylene fibers were not extrudable if highly workable and self-consolidating (CDI < 50), but all mixtures containing the CS fibers were extrudable, independent of workability. The selected design contained both types of fibers, each at 0.9 kg/m^3 (1.5 lb/yd^3).

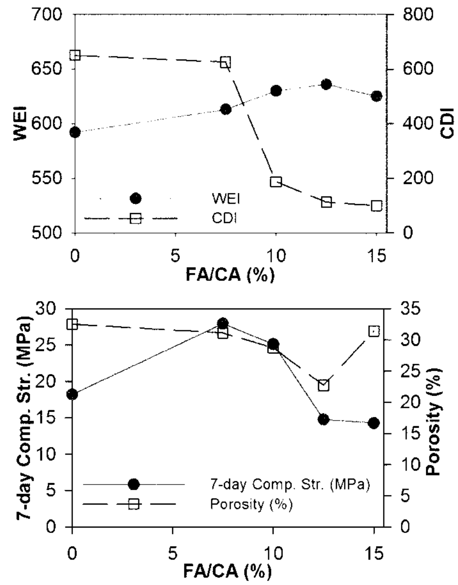

Fig. 3—Effect of FA content on workability, strength, and porosity. (Note: 1 MPa = 145 psi.)

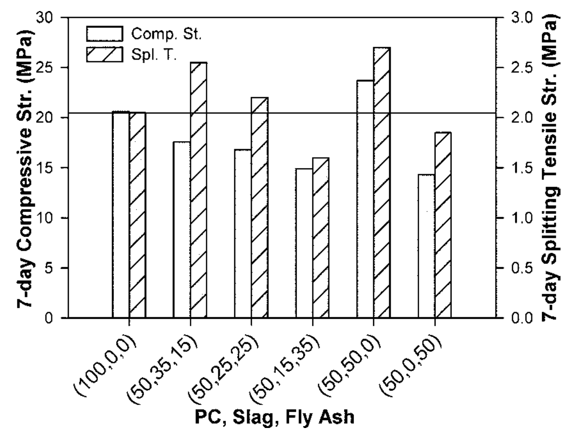

*Fig. 4—Effects of SCMs on strength (B24("x")-S10-CS1.5-*w/c*0.29). (Note: 1 MPa = 145 psi.)*

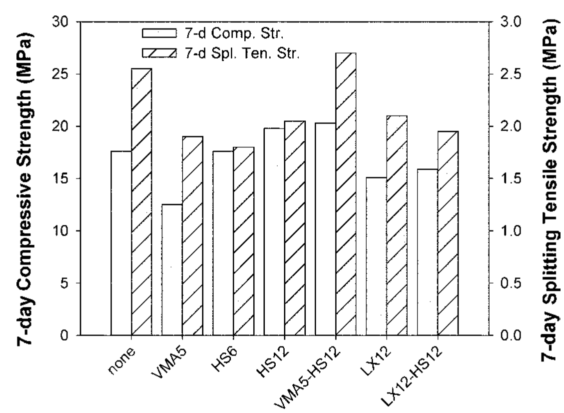

*Fig. 5—Effect of admixtures on strength (B24(50,35,15)-S10-CS1.5-*w/c*0.29). (Note: 1 MPa = 145 psi.)*

Once the primary components of aggregate type, binder content, *w/c*, and sand content were selected, additional mixture variables were investigated. A range of binary and ternary cementitious material combinations were investigated up to a 50% replacement for portland cement. The SCMs

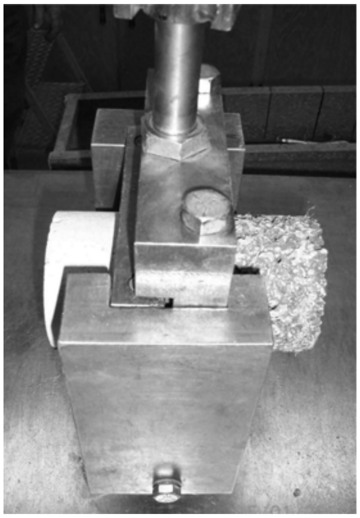

Fig. 6—Overlay bond strength test setup.

included Class C fly ash and Grade 120 ground-granulated blast-furnace slag. Mixture iterations were based on 7-day strengths due to the opening criteria of pervious concrete being cured for 7 days before the removal of the plastic. Due to the slower strength development rates, higher SCM replacement rates were not investigated. Figure 8 shows the workability responses of the SCM mixtures, where the numbers in brackets represent the percentage of portland cement, slag, and fly ash, respectively. All SCM combinations were more workable and required less additional compaction than the 100% portland cement mixture. Also, all SCM combinations containing at least 25% slag had higher 7-day tensile strengths and similar compressive strength values as the 100% portland cement mixture (Fig. 4). The highest 7-day compressive and tensile strengths were achieved by the mixture containing 50% slag of 23.7 and 2.7 MPa (3440 and 390 psi), respectively. The mixture containing 35% slag and 15% fly ash had a lower 7-day compressive strength of 17.6 MPa (2554 psi) but a similar tensile strength of 2.6 MPa (370 psi). Due to the potential for greater long-term strength gain from the fly ash, a ternary blend of 35% slag and 15% fly ash was selected.

The final mixture options for investigation were the admixture combinations (Fig. 5). Other admixtures tested were in addition to the standard admixtures for field-placed pervious concrete of polycarboxylate HRWRA, AEA, and HS. The admixtures and combinations included single and double dosages of the HS—with and without a VMA—and an LX modifier for concrete block mixtures. The mixture containing the VMA and double the recommended dosage of HS had the highest 7-day tensile strength of 2.7 MPa (390 psi). Both latex combinations produced similar 7-day tensile strengths of approximately 2.1 MPa (300 psi). The latex mixtures were cured in the humidity chamber for 7 days, removed from the humidity chamber and allowed to dry for 7 days, and then placed back into the humidity chamber for the remaining curing time. The drying cycle allowed for the formation of the secondary latex film system; however, the 7-day values for the latex mixtures did not allow for drying time and had lower strengths than the mixtures without latex. At 28 days, after drying, the latex samples had higher compressive and tensile strengths than the mixtures without latex. One set of mixture proportions was selected and produced with two admixture schemes—with and without the LX additive.

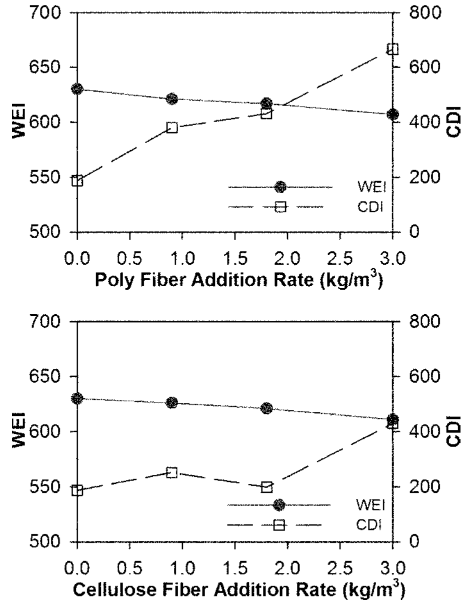

Fig. 7—Effect of fiber type and addition rate on workability. (Note: 1 kg/m^3 = 1.69 lb/yd^3.)

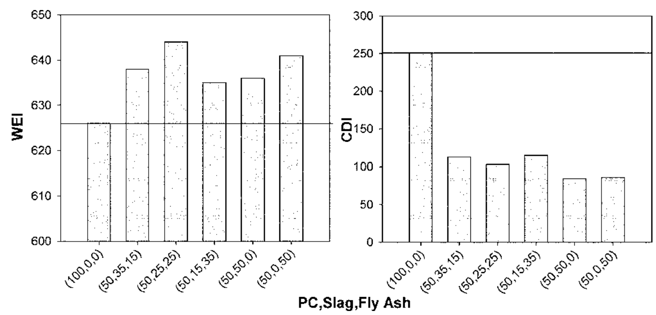

*Fig. 8—Effects of SCMs on workability (B24("x")-S10-CS1.5-*w/c*0.29).*

Overlay bond strength

Fresh PCPC samples were placed over hardened concrete without any vibration or compaction to represent the lowest anticipated bond strength. Four different surface preparation techniques were used on both of the selected mixtures: 1) a clean and dry concrete surface; 2) an LX applied as a tack coat and topped with fresh concrete while tacky; 3) a standard mortar surface grout; and 4) a polymer mortar surface grout (Table 6). Five samples of the clean and dry combination were placed and all other combinations had four samples. Generally, bond strength values were highly variable, indicating that more samples are required for any statistical determination. The grouted samples had the highest bond strengths with the non-latex polymer concrete having higher strength. The latex polymer had better bond strength on the clean and dry concrete than the mixture containing the VMA. The polymer tack coat did the opposite as expected and prevented bonding of either PCPC mixture.

Selected PCPC mixture and properties

Based on the test results and analysis, the aggregate and mixture proportions for the PCPC overlay project were determined. A crushed granite CA containing 18% passing the 4.75 mm (No. 4) sieve was selected. The selected mixture contained a B/A of 24%, a *w/c* of 0.29, an additional FA/CA

Table 6—Bond strength testing results

Mixture	Bond type	Strength, MPa (psi)	Bond type	Strength, MPa (psi)	Bond type	Strength, MPa (psi)	Bond type	Strength, MPa (psi)
Non-latex polymer	Clean and dry	0.04 (6)	Latex polymer tack coat	0.04 (6)	Grout	1.21 (175)	Latex polymer grout	0.86 (125)
		0.13 (19)		0.05 (7)		2.00 (290)		1.58 (327)
		0.14 (20)		0.06 (9)		2.02 (293)		2.35 (341)
		0.25 (37)		—		2.65 (385)		—
		0.32 (47)		—		—		—
	Average	0.27 (26)	Average	0.05 (7)	Average	2.22 (323)	Average	1.83 (265)
	Standard deviation	0.11 (16)	Standard deviation	0.01 (2)	Standard deviation	0.37 (54)	Standard deviation	0.69 (100)
	COV, %	62	COV, %	22	COV, %	17	COV, %	39
Latex polymer	Clean and dry	0.15 (22)	Latex polymer tack coat	0.05 (7)	Grout	0.55 (80)	Latex polymer grout	1.20 (174)
		0.34 (49)		—		1.24 (180)		1.23 (178)
		0.62 (90)		—		1.43 (207)		1.50 (217)
		1.22 (177)		—		2.24 (325)		2.76 (401)
		1.48 (215)		—		—		—
	Average	0.76 (111)	Average	—	Average	1.36 (198)	Average	1.67 (243)
	Standard deviation	0.57 (83)	Standard deviation	—	Standard deviation	0.70 (101)	Standard deviation	0.74 (108)
	COV, %	75	COV, %	—	COV, %	51	COV, %	44

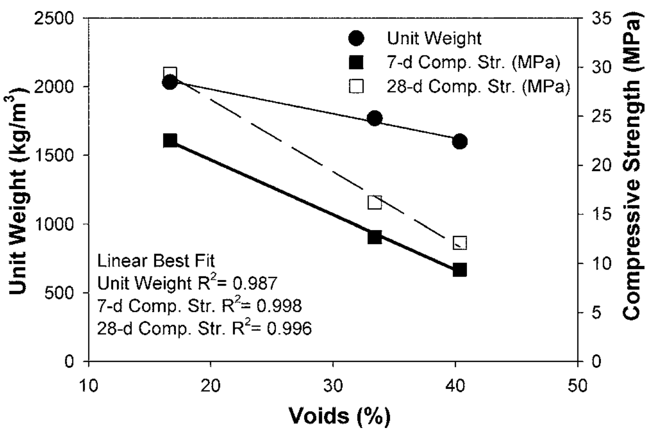

Fig. 9—Compaction density relationships. (Note: 1 MPa = 145 psi; 1 kg/m^3 = 1.69 lb/yd^3.)

Fig. 10—Laboratory testing of selected mixture.

of 10%, 0.9 kg/m^3 (1.5 lb/yd^3) of both short-graded PS and CS microfibers, and had 35% slag and 15% fly ash replacing portland cement. The non-latex additive mixture had HRWRA, AEA, HS, and VMA, whereas the latex mixture contained a latex concrete block additive, HRWRA, AEA, and HS. Complete test results for the mixtures are shown in Table 5.

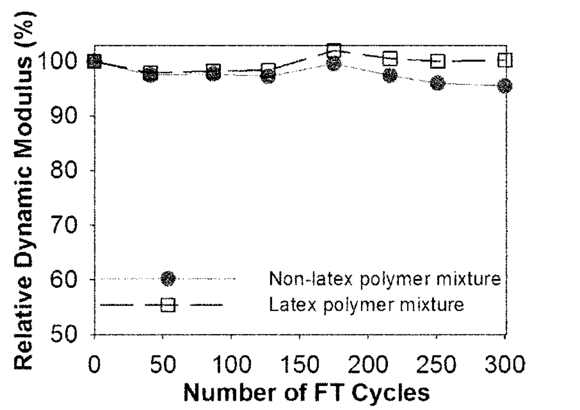

Fig. 11—Freezing-and-thawing durability of selected mixtures.

Considering the construction schedule and timing of future pervious overlay projects and the additional steps required for pregrouting the surface, the final design was overlaid on a clean and dry concrete surface. The compaction density relationships for the selected mixture are shown in Fig. 9. As expected, unit weight and strength are linear with respect to voids, as was tensile strength. Permeability exponentially increased with voids from 0.08 cm/s (288 in./h) at the 17% void sample to over 2 cm/s (7500 in./h) at the 40% void samples. Figure 10 shows an initial trial of the concrete overlay in the laboratory. The sample was placed using a nonvibrating slipform grout box mini-paver. The test pavement was 400 mm (18 in.) wide and 100 mm (4 in.) thick, placed on a clean concrete surface. More information on the mini-paver setup can be found in Wang et al.[26] The sample was self-consolidating, porosity was uniform across the section profile, and it had good edge-holding ability. After selecting the mixture constituents, testing workability, determining the compaction density relationships, and investigating porosity from the slipforming process, the final mixture had a design void content of 22.5%.

Freezing-and-thawing and surface durabilities

The freezing-and-thawing durability of both mixtures is shown in Fig. 11, placed at the design void content of 22.5%.

Each point represents an average of three test samples with a COV of less than 10%. The mixtures were demolded after 24 hours and placed in a 100% humidity fog room until testing began at 56 days, except for the previously mentioned latex curing procedure. The latex polymer mixture had a durability factor of 100 and the non-latex mixture had a durability factor of 95. Both mixtures had excellent freezing-and-thawing performance. Between 150 and 175 cycles, the samples were paused by placing the frozen samples into a laboratory freezer for 2 weeks to accommodate testing schedules. Pausing in a frozen state is approved within ASTM C666 (A)[20]; however, a slight change in the RDM response was observed.

Surface abrasion resistance was measured on the freezing-and-thawing specimens before and after testing. The latex polymer mixture had slightly higher abrasion than the non-latex mixture. Surface abrasion on pervious concrete is highly dependent on the CA type and testing results are limited; however, abrasion results were 5 to 7% lower than the best performing pervious concrete mixture reported in the literature[27] containing river gravel and no SCMs.

Field construction and performance

Overlay construction occurred in October 2008. The original pavement was sandblasted and cleaned prior to wetting before the overlay placement. The placement air temperature ranged from 4 to 12°C (40 to 54°F). Upon arrival, the concrete temperature and unit weight was tested before placing. Lanes were placed individually 2 weeks apart due to contractor availability. Slabs were cured under two layers of plastic sheeting for 7 days. To date, the overlay has experienced over 10,000 passes of the 36,300 kg (80 kip) testing vehicle. The most common distress reported in the field condition surveys is joint deterioration caused by the joint-forming process. Using standard sounding techniques, the presence of debonding was difficult to identify. The section will be continuously monitored for the formation of cracks, indicating debonded locations.[28] The average field infiltration rate was greater than 0.70 cm/s (1000 in./h) according to ASTM C1701,[27] with no noticeable decrease between the initial and current condition.[29,30] On-board sound intensity (OBSI) measurements, developed for highway pavements, resulted in an initial average of 98 dB. Subsequent values after additional traffic have averaged 94 dB.[30] Concrete pavements 100 dB or lower are typically considered quiet pavements and only 12% of the longitudinally tined pavements and 4% of the transversely tined pavements are considered quiet.[31] Sound levels in the low-to-mid 90s makes the pervious concrete overlay one of the quietest concrete pavements ever tested in the U.S.

CONCLUSIONS

A systematic study was conducted to investigate the effects of a wide variety of concrete materials and mixture proportions on PCPC performance. The results of the study were used for selecting a suitable PCPC mixture for the first pervious concrete overlay project in the U.S. The results indicate that PCPC mixtures can be designed to be highly workable, sufficiently strong, permeable, and have excellent freezing-and-thawing durability, thus being suitable for pavement overlays. The detailed conclusions resulting from this study are:

1. The modified gyratory test is a valuable method for evaluating the materials and mixture proportions used for highly workable pervious concrete.
2. Increased mortar content improves both workability and strength of pervious concrete.
3. The addition of CS fibers had a limited impact on the initial workability of pervious concrete but significantly improved the edge-holding ability of the mixture, thus proving suitable for slipform construction.
4. The use of 35% slag and 15% Class C fly ash provided PCPC with good early-age and long-term performance.
5. Certain admixtures (HRWRA, HS, and AEA) are required to achieve the workability needed to achieve proper density and durability.
6. The selected PCPC mixture for the pavement overlay project demonstrated excellent freezing-and-thawing durability (with a durability factor above 95).
7. To date, the constructed durability has been good with few distresses, whereas the pavement appears extremely quiet with OBSI values in the mid-90 dB range.

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