Preliminary Procedure for Structural Design of Pervious Concrete Pavements

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Preliminary Procedure for Structural Design of Pervious Concrete Pavements

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<tr><td colspan="4">16. ABSTRACT
Pervious concrete (PC) is a pavement material that provides a porous medium to facilitate the infiltration of stormwater to the underlayers. With the increasing use of PC pavement nationwide, the mechanical properties of the material need to be established. To do so, PC specimens were prepared in various porosities, using two aggregate types. Hardened porosity, compressive, and flexural strength tests were carried out on all PC specimens. The test results from this study were supplemented by the results from past research studies conducted at Washington State University as well as those from literature to develop multi variable linear regression models to predict strength properties for pavement thickness design. Multi variable linear regression relationships between the PC compressive and flexural strength, hardened porosity, and mixture design parameters were established.
Additionally, a recommended thickness design database was developed for low-traffic-volume PC pavements with different mechanical properties and under various traffic volumes and axle load configurations. The fatigue model for conventional Portland cement concrete was used to obtain the maximum allowable load repetitions for PC slabs with three different moduli of rupture. To obtain the fatigue life of PC, four traffic categories and axle loads were obtained from the American Concrete Institute (ACI)'s guide on the design of concrete parking lots. The applied stress by each axle load on PC slabs was obtained using a previously validated finite element model. Using the applied stress and different flexural strength values of PC, the fatigue life of PC slabs with various thicknesses and mechanical properties was generated. Based on the calculated fatigue life and the traffic volumes specified by ACI, a thickness design table was developed. The proposed thickness design table needs to be updated using a fatigue model for pervious concrete.</td></tr>
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EXECUTIVE SUMMARY

Objectives

In this project, the aims was to establish the mechanical properties of commonly used pervious concrete (PC) mixtures for pavement thickness design. Based on the test results of this study and previous projects, statistical analyses were conducted on the results of the mechanical tests conducted on PC mixtures to obtain regression models that relate compressive and flexural strengths to hardened porosity/density and other mixture design parameters. The final objective is to develop a thickness design database for PC pavements using different mechanical properties for different levels of traffic volumes and axle load configurations that are suitable for PC pavements common applications.

Background

PC is a no-fines mixture that contains anywhere from 15 to 30 percent volumetric air void fraction. The main role of this class of concrete is to provide rapid infiltration of surface runoff while serving as a pavement for vehicular and pedestrian traffic. Due to its highly porous nature, the mechanical properties of PC are different than those of conventional portland cement concrete (PCC). Therefore, the established correlations between different properties of conventional PCC (such as the correlation between compressive and flexural strength) are not applicable to PC. The emergence of PC as a pavement material for parking lots and low traffic volume roads raised the need for relationships that correlate the mechanical properties with measurable properties such as hardened porosity, especially for layer thickness design purposes.

Research Activities

PC mixtures were prepared at the Concrete Material Characterization Laboratory in Washington State University (WSU) using two mixture designs and two types of coarse aggregate. The fresh PC was cast into 6×12-inch (diameter by height) cylinders and 4×4×14-inch beams. Upon casting, all the specimens were sealed and left to cure in the laboratory's ambient conditions. Hardened porosity testing was carried out on all PC specimens upon demolding at 7-day age. In addition, 28-day compressive and flexural strength tests were conducted on PC cylinders and beams, respectively. The mechanical test results of PC were combined with the results from previous projects conducted at WSU and those results found in literature. A statistical analysis was conducted to derive relationships between the mechanical properties of PC and the mixture design variables.

In the absence of a fatigue model for PC, the current fatigue model developed for conventional PCC was used to establish the fatigue life of PC with different mechanical properties (N_f). The fatigue life results were used to develop a suggested thickness design table for PC under various traffic loads. The traffic loads were derived from four anticipated traffic categories, specified by the American Concrete Institute (ACI) for parking lots and service lanes, where PC is mostly used. The developed thickness table needs to be updated in the future using a fatigue model suitable for PC materials.

Conclusions

The mechanical test results showed that hardened porosity of PC substantially affected both compressive and flexural strength. In addition, increasing the cement content while keeping the water-to-cement ratio did not yield a substantial effect on the compressive and flexural strength of PC as they were controlled mainly by hardened porosity. Furthermore, crushed aggregate produced PC with porosity higher than 20 percent while round aggregates produced PC with porosity less than or equal to 20 percent. Using the mechanical test results from this project, as well as the data from past projects and form the literature, a statistical analysis was carried out and multi variable linear regression models were developed to relate the PC compressive and flexural strengths to the different mixture design variables.

Additionally, recommended design thicknesses for low-traffic-volume PC pavements were developed based on a fatigue model for conventional concrete with four traffic categories adopted from the ACI guide for design of conventional concrete parking lots. The proposed design thicknesses will help designers to evaluate the required PC pavement thickness based on the expected traffic volume and PC mechanical properties, but needs to be updated using a fatigue model for pervious concrete.

1. INTRODUCTION

Pervious concrete (PC) pavements have gained popularity due to advantages as stormwater drainage systems. However, as opposed to the hydrological performance, structural behavior of PC pavements requires further investigation to develop mechanistically established pavement layer thicknesses.

This report describes the efforts taken towards the development of a database of mechanical properties for PC specimens made from a pool of different mixture designs incorporating different aggregate types. The financial support provided by the Washington Department of Transportation (WSDOT) for this project made it possible to extend an ongoing research project sponsored by the American Concrete Institute (ACI)'s Concrete Research Council (CRC), which focused on developing a fatigue model for PC mixtures. As part of the extension, mechanical properties, 28-day compressive strength (f'_c) and flexural strength (M_R) were characterized for a variety of PC mixtures. These parameters are minimum requirements for the pavement structural layer thickness design. Relationships were developed to correlate the mechanical properties with readily available properties of PC such as hardened porosity and mixture design proportioning.

The mixture design details, results of the material property testing, and the analysis of the test results are discussed in this report. Furthermore, the report introduces a preliminary layer thickness table for PC pavements with various properties at various traffic levels, which needs to be updated in the future using a fatigue model for PC.

2. MATERIALS AND TEST METHODS

Mixture design selection

Coarse aggregate gradation and mixture designs used in this project were selected to represent the current state of practice for PC production across Washington State. To do so, the coarse aggregate gradations and PC mixture designs were collected from several ready-mix concrete producers. Aggregate gradations from different sources are plotted in Figure 1. As specified in PC specifications set forth by WSDOT, the American Association of State Highway and Transportation Officials (AASHTO) Grading No. 8 aggregate limits are also shown in Figure 1 (WSDOT, 2016). The aggregate gradation from all sources are within the AASHTO No. 8 limits and are relatively similar in particle size distribution except for one producer.

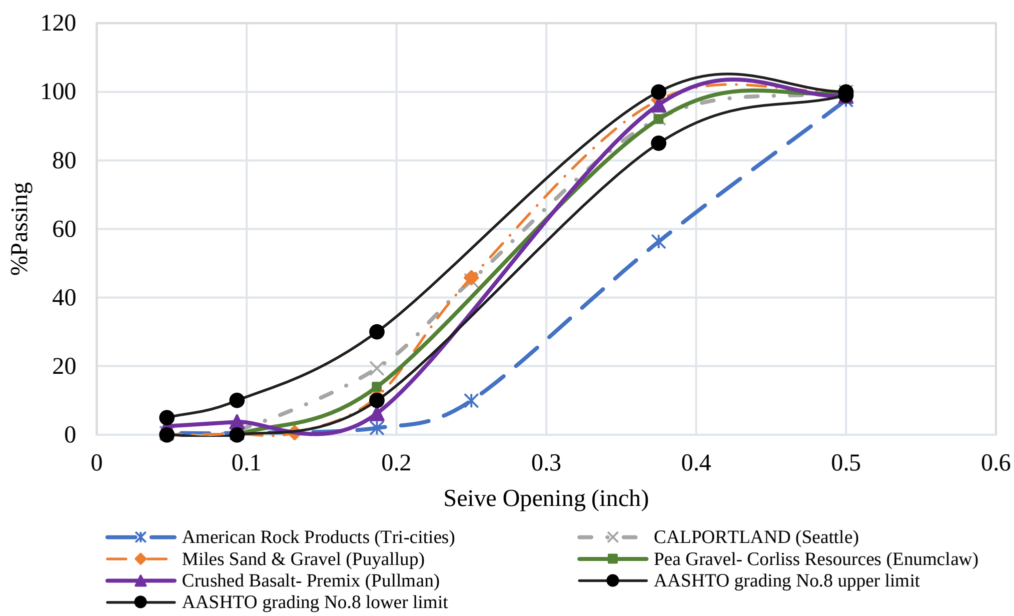


Figure 1. Gradation curves from different aggregate sources in Washington State

Once it was concluded that gradation was consistent among producers of PC, enquiries were made regarding the types and shapes of the used coarse aggregates. Two distinct types of aggregates were identified across the state and were used in this project: crushed basalt (from Premix in Pullman, WA) and pea gravel (from Corliss Resources in Enumclaw, WA) (Figure 2). The gradation of the two aggregates were previously shown in Figure 1. The maximum aggregate size for both aggregates is 3/8 inch.

(a) (b)

Figure 2. Photos of samples from the (a) crushed basalt; (b) pea gravel aggregates used in the study

These two aggregates were selected based on laboratory trial mixtures, which revealed that pea gravel was able to successfully produce PC with porosities of 20 percent and below, while PC with higher porosities can be produced by the crushed basalt aggregate. Two example cylinder specimens cast from each mixture is shown in Figure 3.

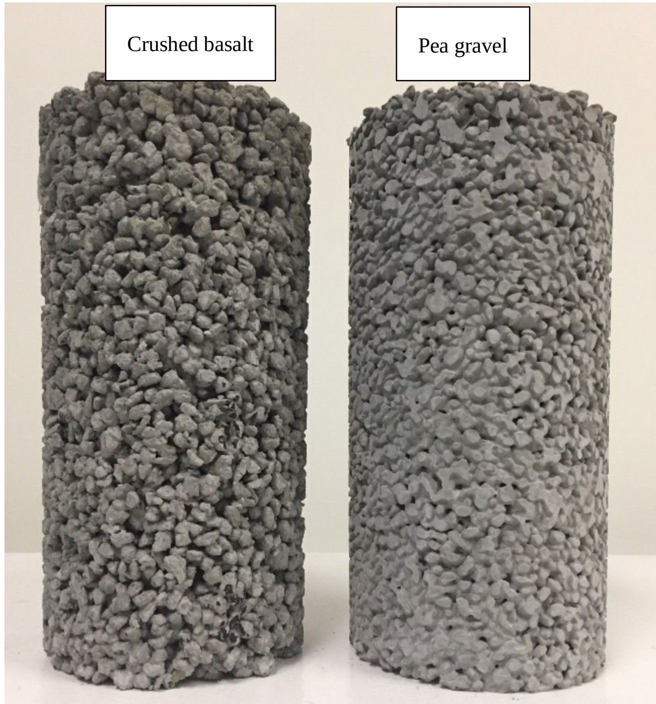


Figure 3. Example PC specimens made for PC mixtures containing crushed basalt and pea gravel aggregates

Additionally, the mixture design of PC used by different concrete producers in Washington State were collected to select a representative mixture design that is commonly used. Table 1 shows the different mixture designs used by producers in Washington State.

Table 1. PC mixture designs from different producers in Washington State

Producer in WA	Location	Coarse Aggregate (lb/yd^3)	Cement (lb/yd^3)	Water (lb/yd^3)	Water/ Cement	Aggregate/ Cement
Premix	Pullman	2,602	459	158	0.34	5.67
American Rock Products	Tri-cities	2,804	520	160	0.30	5.39
CalPortland	Seattle	3,000	385	140	0.36	7.79
Miles Sand & Gravel	Puyallup	2,720	525	150	0.29	5.18
Corliss Resources	Enumclaw	2,765	480	166	0.34	5.76
Average	-	2,778	474	155	0.33	5.95

Based on the mixture designs in Table 1 and the specifications by WSDOT for PC production, four mixtures were included in this study as shown in Table 2. The four mixtures contained two cement contents: 480 and 520 lb/yd^3. The mixture with 480 lb/yd^3 cement content had a water content of 163 lb/yd^3 (labeled as PC-1, hereafter), while the mixture with 520 lb/yd^3 cement content had a water content of 177 lb/yd^3 (PC-2). The water-to-cement ratio (w/c) was kept constant at 0.34 for all mixtures, which is close to the average w/c in Table 1 and is also the value specified in WSDOT's specification (WSDOT, 2016). Ordinary Portland cement Type I/II from Ash Grove Cement was used in all mixtures. The mixture designs used in this project are listed in Table 2.

Table 2. The Four Select Mixture designs used in the study

Mixture Design	PC-1	PC-2
Mixture design for 25 and 30% porosity level using Crushed Basalt		
Coarse Aggregate lb/yd^3	2,700	2,700
Cement Type I/II (Ash Grove) lb/yd^3	480	520
Water lb/yd^3	163	177
VMAR (W.R. Grace & Co.) oz/yd^3	39	39
Recover (W.R. Grace & Co.) oz/yd^3	38	38
Mixture design for 20% and below porosity level using Pea Gravel		
Coarse Aggregate lb/yd^3	2,765	2,765
Cement Type I/II (Ash Grove) lb/yd^3	480	520
Water lb/yd^3	163	177
Delvo (BASF) oz/yd^3	52	52

As shown in Table 2, from each of the two mixture designs, specimens were cast at three target porosity levels: 20, 25, and 30 percent. As stated previously, the pea gravel was used to achieve the 20 percent target porosity and the crushed basalt aggregate provided for higher porosities. The pea gravel aggregate content in PC-1 and PC-2 mixtures was similar to the aggregate content used in the PC mixture design (Table 1) of Corliss Resources Inc. (the source of pea gravel aggregates used in this project).

Mixing, fresh properteies, and specimen casting

PC was mixed according to the specifications of the American Society for Testing and Materials (ASTM) C192 (ASTM, 2016). Prior to placing the PC in the molds, the fresh density of the mixture was established as specified in ASTM C1688 (ASTM, 2014) (Figure 4). PC was used to cast 4×4×14-inch beams as well as 6×12-inch cylinders (Figure 5).

The measured fresh density was used to obtain the required mass of the PC in each mold to achieve the desired porosity for each specimen. Additionally, the required PC mass was placed into the beam molds in two equal lifts and into the cylinder molds in three equal lifts. A Standard Proctor Hammer was used to compact PC in the beam molds and a rubber mallet was used to strike the cylinder molds on all sides until the desired compaction level was achieved. Specimen's surface was finished using a float as illustrated in Figure 5. Three beams and at a minimum, three cylinders were cast at each targeted porosity level. Nine beams and eleven cylinders were cast for both PC-1 and PC-2 mixtures. In total, 18 beams and 22 cylinders were cast. All PC specimens were sealed using plastic wrap and cured in laboratory ambient condtions.

Figure 4. Photos show the process to establish fresh density of PC

Figure 5. Photo on the left: using proctor hammer to compact PC specimen, photo on the right: finishing PC specimens using a float

Hardened porosity testing

Hardened porosity tests were carried out for all PC specimens in accordance with ASTM C1754 (ASTM, 2012) (Figure 6). The test was conducted by first measuring the dry weight of the specimens (M_d). Then, the dimensions of the specimens (height and diameter) were recorded to obtain the volume (V). To do so, two caliper measurements were taken at mid-depth to obtain the diameter, followed by two height measurements. Hardened density was calculated as the ratio of the dry mass to the volume of the specimen (M_d/V). To characterize porosity, each specimen was submerged in water for at least 30 minutes, after which the submerged mass of each specimen was recorded (M_W). The volume of the solids was obtained by dividing the difference between the dry and submerged weights by the density of water (ρ_w). Subsequently, porosity (P) was calculated using Eq. 1.

$$P = [1 - \left(\frac{M_d - M_w}{\rho_w * V}\right)] \times 100 \quad \text{Eq. 1}$$

Figure 6. Hardened porosity test setup where the mass of submerged PC specimen is measured

Mechanical properties testing

In the lack of a standardized test procedure for PC, 28-day compressive and flexural strength tests were conducted on three PC specimens for each porosity level in accordance with ASTM C39 (ASTM, 2017) and ASTM C293 (ASTM, 2016), respectively (Figure 7). The loading rates of compressive and flexural tests defined for traditional PCC needed to be adjusted to compensate for the lower strength of PC and to provide a reasonable test duration per specimen with a steady no-shock loading. The loading rates used in compressive and flexural strength tests of PC specimens were 10 psi/second and 0.006 inch/minute, respectively. These loading rates provided a gradually and steadily (no-shock) increasing load suitable for PC and yielded reasonable results.

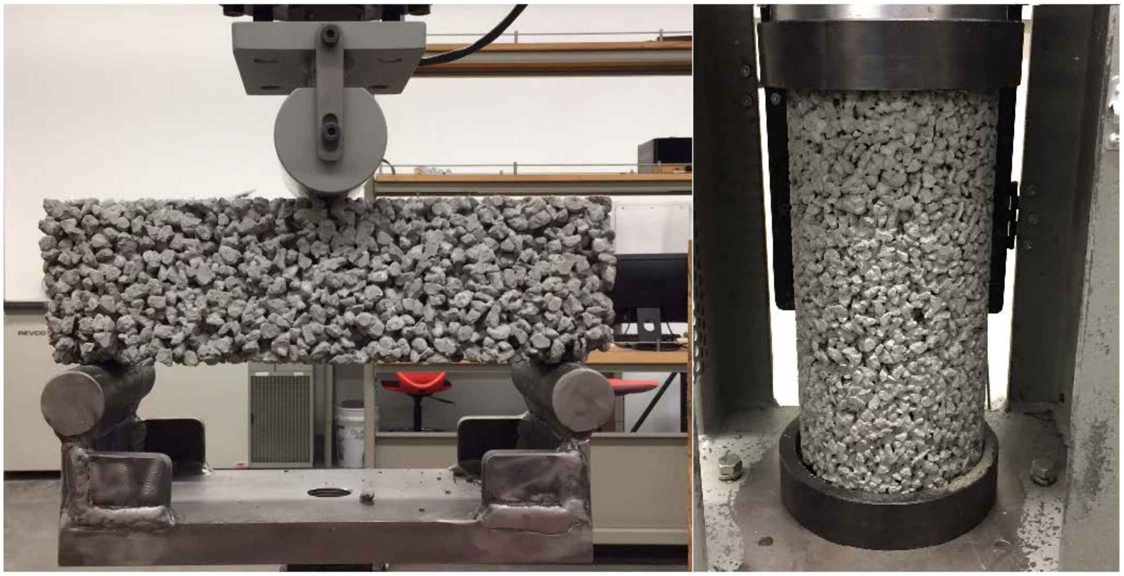


Figure 7. Flexural strength (left) and compressive strength (right) test set up for PC specimens

3. TEST RESULTS

Fresh density and hardened porosity

The fresh densities of the PC mixtures with different cement contents and aggregate types are shown in Figure 8. The increase of the cement and water contents in PC-1 mixture compared to PC-2 mixture increased the average fresh density of PC mixtures made with pea gravel and crushed basalt. A paired t-test was conducted to compare the fresh density data of PC-1 and PC-2 mixtures and the results showed that the difference in average values of fresh density was statistically significant.

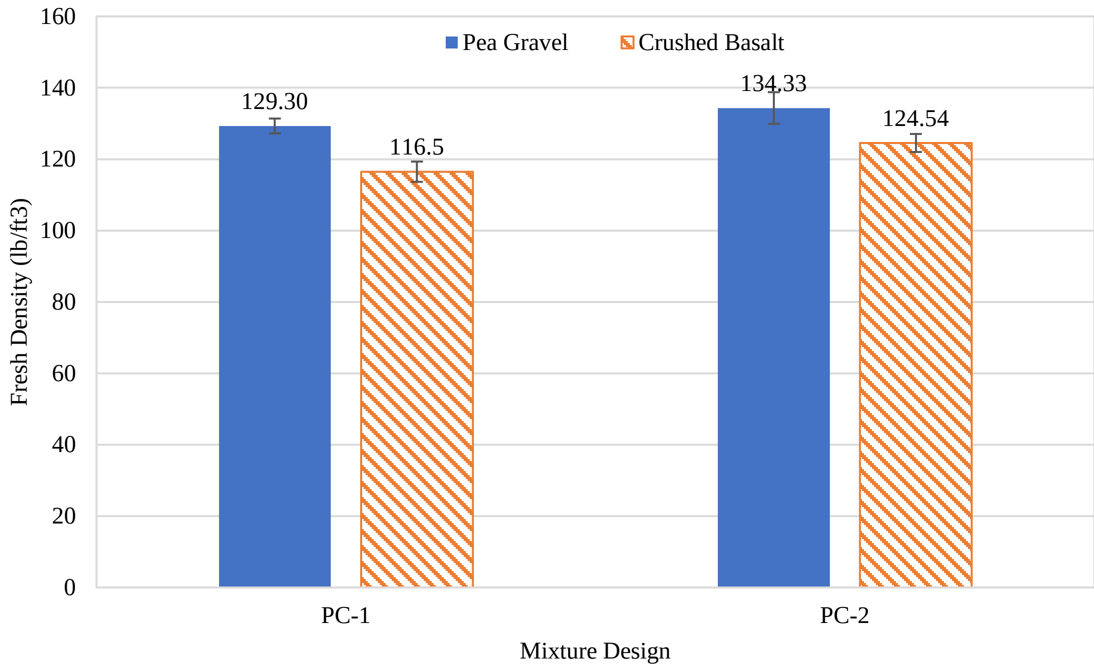


Figure 8. Average fresh density of PC mixtures with different aggregate types

The hardened porosity of PC beams and cylinders from all mixtures are demonstrated in Figure 9 and Figure 10, respectively. In general, PC specimens from all mixtures showed a wide range of porosities at each targeted porosity level. However, PC-2 beams from the mixture with pea gravel a targeted porosity of 20% yielded low porosities due to choking and accumulation of the cement paste on the bottom and side surfaces of the beams; which is caused by excessive compaction which lead to void closure and reduction in porosity.

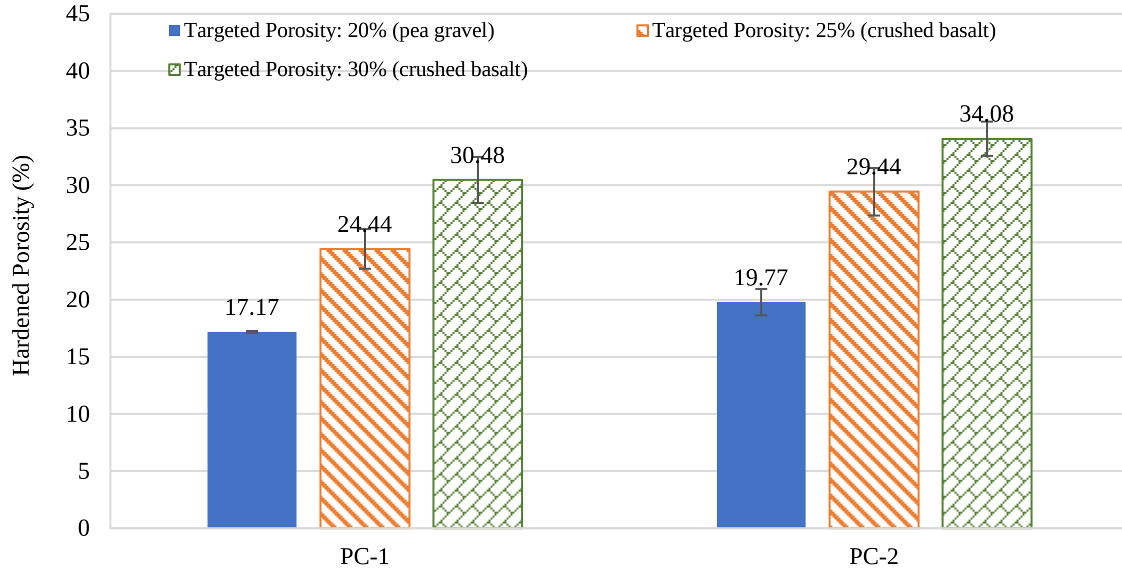


Figure 9. Hardened porosity of PC cylinders with different mixture design and targeted porosity

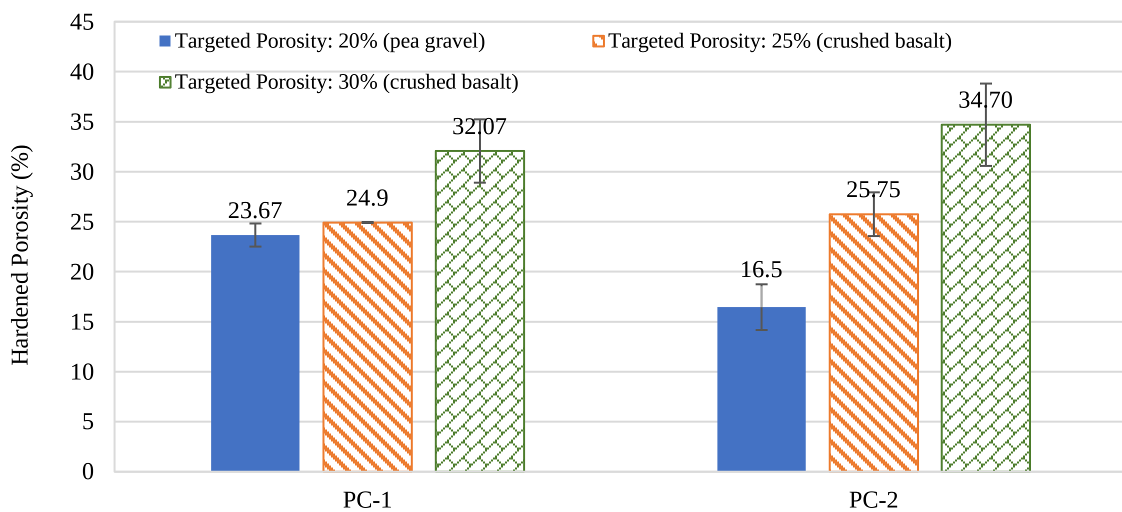


Figure 10. Hardened porosity of PC beams with different mixture design and targeted porosity

Mechanical properties test results

The average 28-day compressive and flexural strength results of PC specimens are shown in Table 3 and Table 4. As mentioned earlier, the two mixtures have the same w/c, relatively similar coarse aggregate contents, but have different cement contents.

Table 3. Average 28-day compressive strength of PC cylinders

Mixture Design ID	Targeted Porosity (%)	28-day Compressive Strength	
		Average Strength (Standard deviation) (psi)	Average Measured Hardened Porosity (Standard deviation) (%)
PC-1	20	2,223 (196)	17.3 (0.1)
	25	1,244 (118)	24.4 (1.7)
	30	1,015 (134)	30.5 (2.0)
PC-2	20	1,519 (132)	19.8 (1.1)
	25	8,16 (113)	29.4 (2.1)
	30	588 (25)	34 (1.5)

Table 4. Average 28-day flexural strength of PC beams

Mixture Design ID	Targeted Porosity (%)	28-day Flexural Strength	
		Average Strength (Standard deviation) (psi)	Average Measured Hardened Porosity (%)
PC-1	20	320 (49)	23.6 (1.1)
	25	348 (23)	24.9 (0.1)
	30	262 (44)	32.1 (0.3)
PC-2	20	405 (28)	16.5 (2.3)
	25	279 (33)	25.7 (2.1)
	30	203 (55)	34.7 (4.1)

Figure 11 and Figure 12 show that the compressive and flexural strength results are sensitive to the hardened porosity of PC specimens. In general, the average porosities of PC-2 specimens were higher than specimens from PC-1, which lead to lower compressive strengths as illustrated in Figure 11.

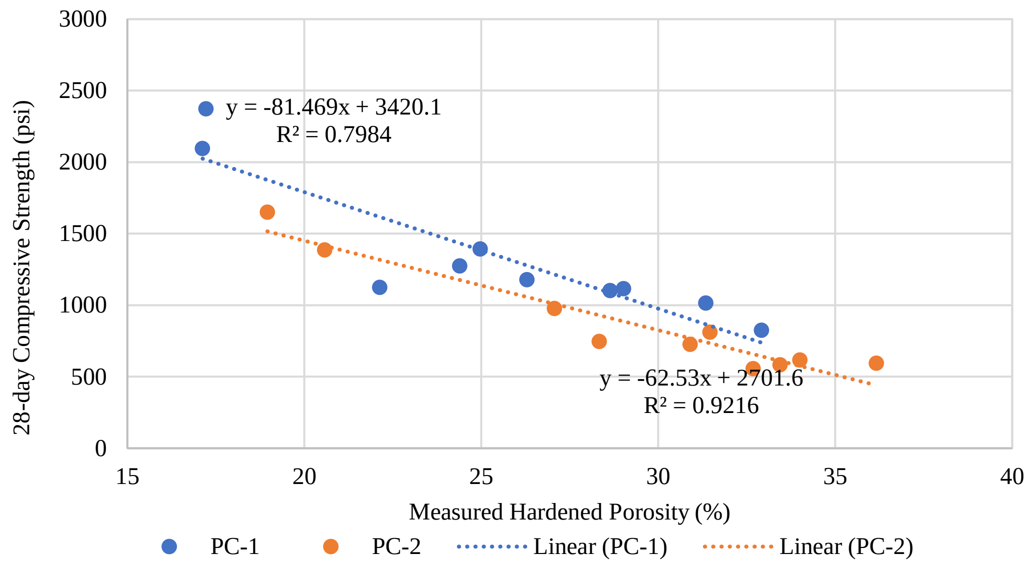


Figure 11. Relationship between hardened porosity and compressive strength of PC specimens for PC-1 and PC-2 mixtures

Similarly, a paired t-test with 95% confidence level was carried out to compare the mean values of compressive strength for PC-1 and PC-2 specimens. The test results showed that the difference between the average values of compressive strength for PC-1 and PC-2 specimens was statistically significant.

Moreover, increasing the cement content from 480 to 520 lb/yd^3 while fixing the w/c ratio did not have a direct effect on the compressive and flexural strength of PC. As seen in Table 4 and Figure 12, the flexural strength of PC-1 and PC-2 specimens were similar on average. A paired t-test was conducted to determine whether the difference in the mean values of flexural strength for PC-1 and PC-2 specimens was statistically significant. The confidence level was selected as 95 percent. A paired t-test revealed that the difference in the mean values of flexural strength of PC-1 and PC-2 specimens was statistically insignificant and therefore, all the flexural strength results were plotted against the hardened porosity as shown in Figure 13.

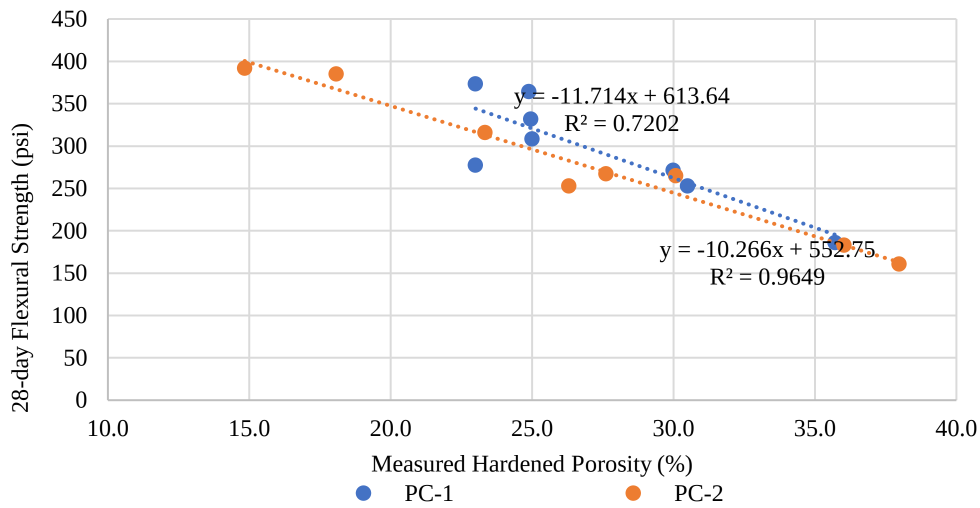


Figure 12. Relationship between hardened porosity and flexural strength of PC specimens for PC-1 and PC-2 mixtures

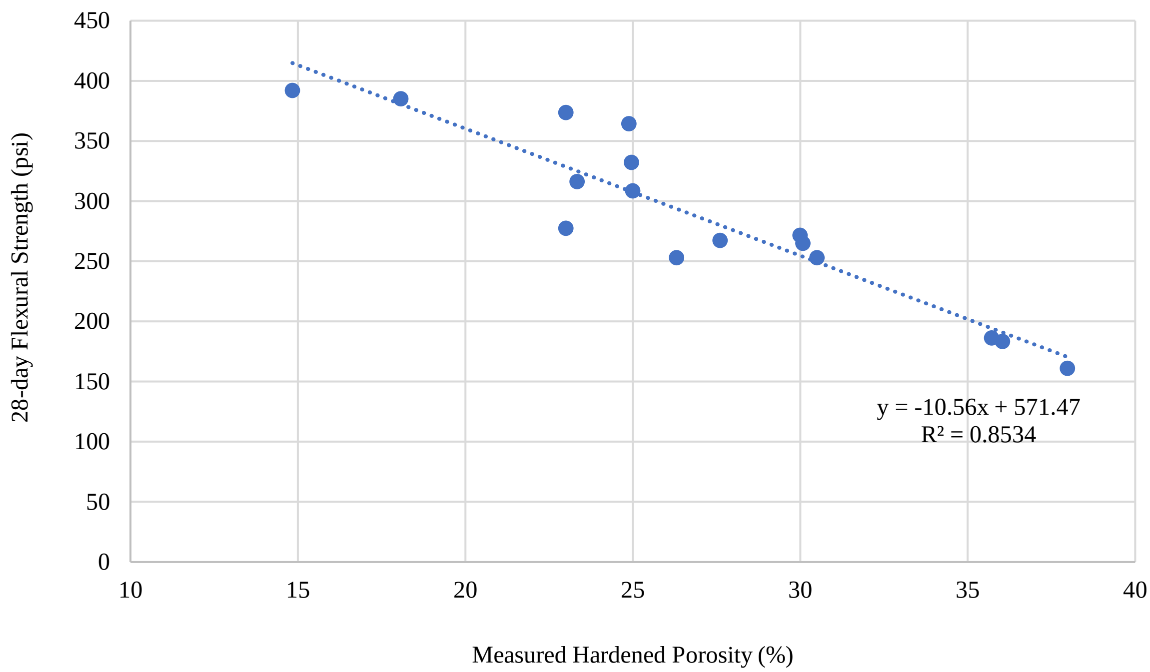


Figure 13. Relationship between hardened porosity and flexural strength of <u>all</u> PC specimens

4. COMPREHENSIVE ANALYSIS OF MECHANICAL PROPERTIES

Statistical analysis and Regression Models

The mechanical test results from this project were combined with similar test results from previous projects conducted at WSU as well as from a study by Ibrahim et al. (2014) to generate a larger database to develop predictive regression models for a wide range of porosity. The mechanical test results data were obtained from testing PC specimens made from six different mixture designs as shown in Table 5. Compressive strength data for 6×12-inch cylinders at 28-day age from this project as well as the specimens from all other mixtures shown in Table 4 were collected and analyzed. Nassiri et al. (2016) reported that 4×8-inch PC cylinders showed higher compressive strength than 6×12-inch PC cylinders for the same mixture design by a factor of 1.13 (Nassiri, Rangelov, & Chen, 2017). Hence, the 28-day compressive strength results of 4×8-inch PC cylinders from all mixtures were divided by 1.13 to obtain the compressive strength of the corresponding 6×12-inch PC cylinders. As a result, the total compressive strength data points from this project and the previous projects was eighty.

Table 5. Mixtures design of PC specimens used in the statistical analysis

Mixture ID	Aggregate (lb/yd^3)	Coarse aggregate size range (inch)	Cement content (lb/yd^3)	Water (lb/yd^3)	w/c
PC-1 WSU 2017	2,700 (crushed basalt)	0.0937 (#8) - 3/8	480	163	0.34
	2,765 (pea gravel)	0.187 (#4) - 3/8			
PC-2 WSU 2017	2,700 (crushed basalt)	0.0937 (#8) - 3/8	520	177	0.34
	2,765 (pea gravel)	0.187 (#4) - 3/8			
PC-3 WSU 2016	2,319 (crushed basalt)	0.0937 (#8) - 3/8	696	189	0.27
PC-4 WSU 2016	2,765 (pea gravel)	0.187 (#4) - 3/8	480	166	0.345
PC-5 WSU 2016	2,893 (river aggregate)	0.0029 (#200) - 3/8	505	71	0.14
PC-6-1 (Ibrahim et al.)	2,697 (crushed limestone)	#4 – 1/2	337	118	0.35
PC-6-2 (Ibrahim et al.)	2,697 (crushed limestone)	3/8 – 1/2	337	135	0.40
PC-6-3 (Ibrahim et al.)	3,033 (crushed limestone)	3/8 – 1/2	253	85.5	0.35
PC-6-4 (Ibrahim et al.)	3,033 (crushed limestone)	3/8 – 1/2	421	147	0.35
PC-6-5 (Ibrahim et al.)	2,528 (crushed limestone)	3/8 – 1/2	253	85.5	0.35
PC-6-6 (Ibrahim et al.)	2,528 (crushed limestone)	3/8 – 1/2	421	147	0.35

The strength and hardened porosity limits for the data used in this report and the mean values for the inputs are shown in Table 6.

Table 6 Max, min, and mean values of the regression variables

Parameter	Upper limit	Lower limit	Mean
Regression parameters for $f'_{c\text{-}28\ day}$ No. of specimens = 80			
Hardened Porosity (%)	42	13	26
Compressive Strength (psi)	3,443	136	1442
Aggregate Content (lb/yd^3)	3,034	2,319	2,755
Cement Content (lb/yd^3)	696	253	464
Water Content (lb/yd^3)	189	71	122
W/C	0.40	0.14	0.27
Aggregate/Cement	5.75	3.35	6.30
Regression parameters for $M_{R\text{-}28\text{-}day}$ No. of specimens = 18			
Hardened Porosity (%)	38	15	27
Flexural Strength (psi)	392	161	294
Aggregate (lb/yd^3)	2,765	2,319	2655
Cement content (lb/yd^3)	696	480	534
Water content (lb/yd^3)	189	163	173
Water/Cement	0.35	0.27	0.33
Aggregate/Cement	5.75	3.35	5.10

A multi variable linear regression analysis was carried out using Minitab statistical software (Minitab17, 2016). The resulting regression model is shown in Eq.2 below. Sensitivity analysis showed that changing porosity in Eq. 2 affects the compressive strength more significantly than changing the w/c ratio and cement content in (Figure 14).

$$f'_{c-28\,day} = 3681 - 78.21\,P - 1903\left(\frac{W}{C}\right) + 0.656\,C \qquad \text{Eq. 2}$$

R^2=92%, Standard Error of Estimate (SEE) = 262, P-value < 0.001

Where P is measured hardened porosity (%), C is cement content (lb/yd^3), and w/c is the water-to-cement ratio.

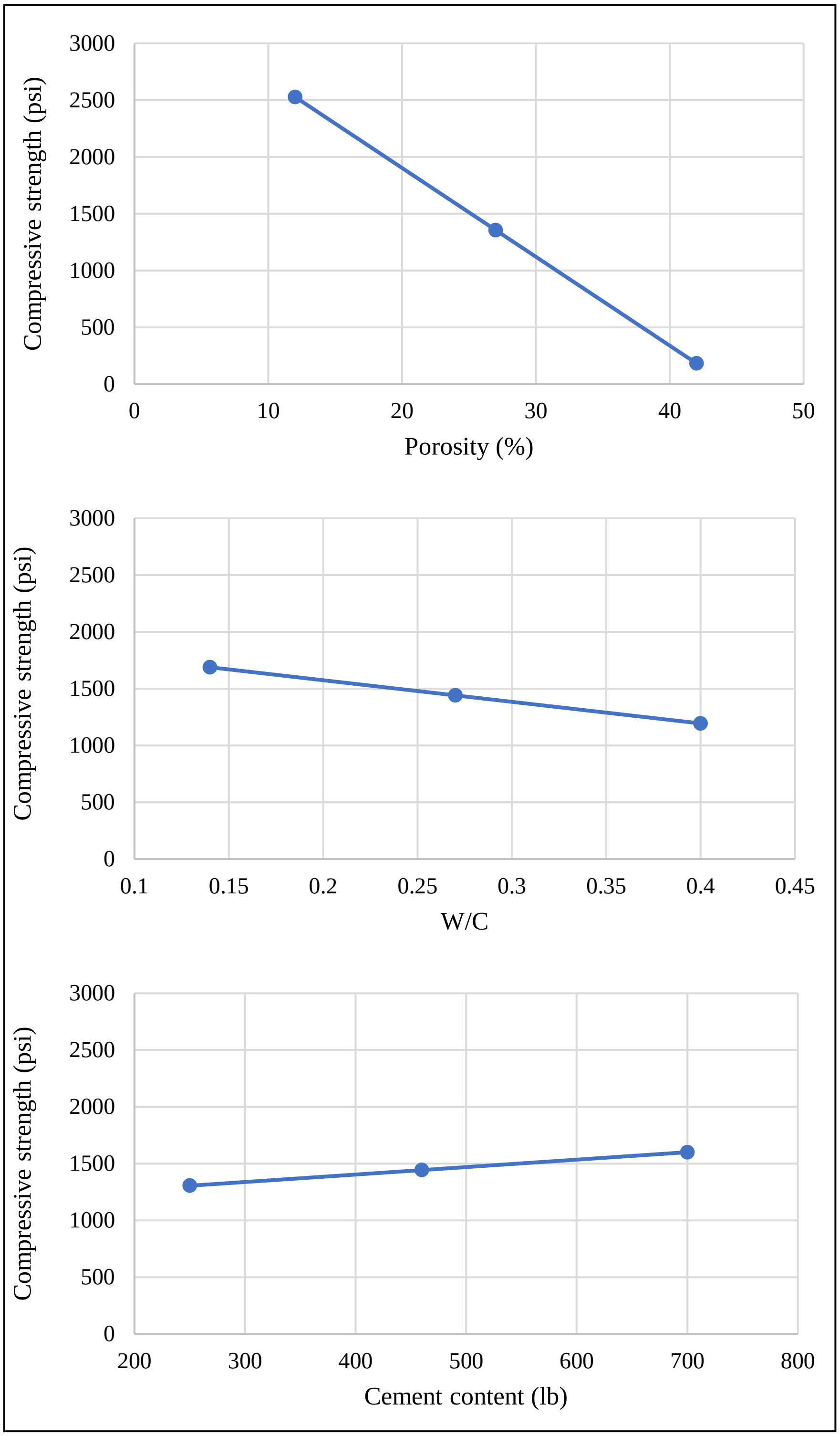


Figure 14. Influence of the regression parameters in Eq.2 to the predicted strength

Similarly, the 28-day flexural strength (M_R) of the 18 PC specimens including the specimens from this project and PC-3 and PC-4 were analyzed and the resulted regression model below. Note that there were no beam specimens cast from PC-5 and PC-6.

$$M_{R\ 28-day} = 751.3 - 10.6\,P - 525\left(\frac{W}{C}\right) \qquad \text{Eq. 3}$$

$R^2 = 83.4\%$, SEE = 27.2, P-value < 0.001

The effect of changing porosity in Eq. 3 yielded a dramatic change in flexural strength of PC compared to the effect of changing w/c (Figure 15). Furthermore, Figure 16 illustrates the relationship between the hardened porosity and compressive strength of PC specimens used in developing the regression model in Eq. 2; while Figure 17 shows the trend between hardened porosity and flexural strength for all PC specimens used in developing Eq. 3. Both figures show that hardened porosity is inversely proportional to the compressive and flexural strength of PC.

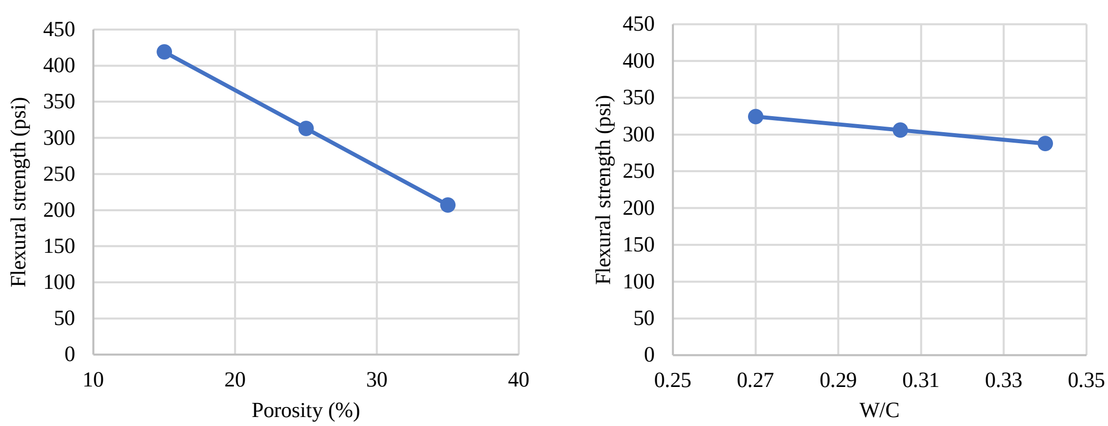


Figure 15. Influence of the regression parameters in Eq.3 to the predicted flexural strength

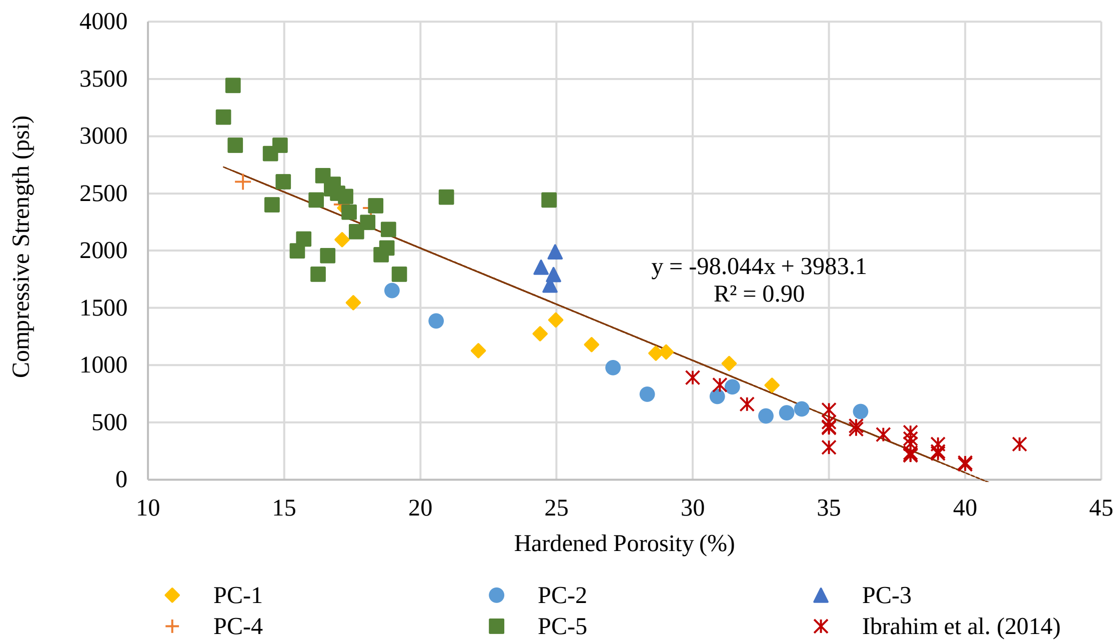


Figure 16. Hardened porosity vs compressive strength of PC specimens from all mixtures

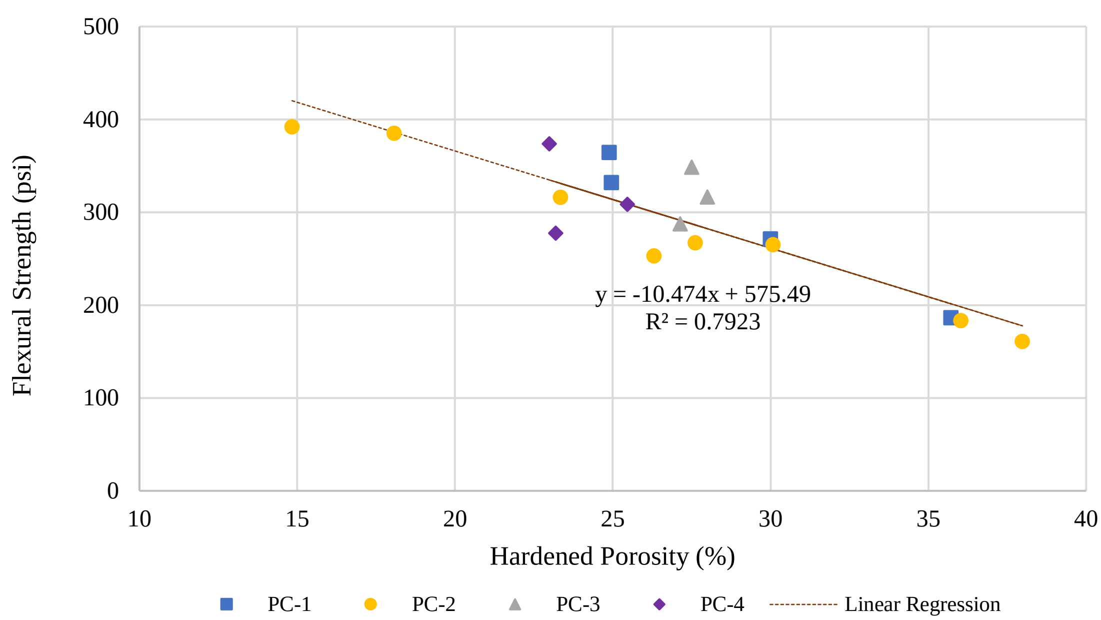


Figure 17. Hardened porosity vs flexural strength of PC specimens from all mixtures

The regression models in Eq. 2 and 3 are only valid within the range of the data used in the study. The limits for the inputs were shown earlier in Table 6. Further, the regression models represent PC made with no supplementary cementitious materials, recycled materials, fine aggregate, or fibers. Further research is required to extend the regression analysis to include a wider range of mixture design parameters.

5. PAVEMENT THICKNESS DESIGN

Overview of Design Approach

This section presents an interim approach for the layer thickness selection for PC pavements using traffic volumes typical for PC pavement applications. Similar to the procedure of designing low-traffic-volume concrete pavements, the failure due to fatigue loading at the slab edge location was used for the design of PC pavements (Vancura, MacDonald, & Khazanovich., 2011; Ghafoori & Dutta, 1995; PCA, 1984). Currently, a fatigue model that can be used to estimate the number of allowable load applications (N_f) is not available for pervious concrete. Therefore, a commonly used fatigue model (Eq. 4) adopted by the American Concrete Paving Association (ACPA) for conventional PCC pavements was adopted to estimate the N_f for PC pavements before failure. In Eq. 4, SR is the ratio of the applied stress to the flexural strength of PC pavement and P is the failure probability.

$$log\left(N_f\right) = \left[\frac{-SR^{-10.24}\,log(1-P)}{0.0112}\right]^{0.217} \quad \text{Eq. 4}$$

To develop a thickness design database for PC pavements, the four traffic categories as show in Table 7 were adopted based on the ACI's Guide for the Design and Construction of Concrete Parking Lots (ACI 330R-08, 2008).

Table 7 Traffic categories anticipated to occur on low traffic volume PC pavements (ACI 330R-08, 2008)

Traffic categories	Description
Category A	Car parking areas and access lanes
Category B	Shopping center entrance and service lanes; city and school buses parking areas and interior lanes; Truck parking areas
Category C	Entrance and exterior lanes; Truck parking areas
Category D	Truck parking areas

For each traffic category, the axle loads in ACI 330R-08 (Table 8) were used to obtain the applied stress on PC slabs with different thicknesses and flexural strength using ISLAB2005, which is a finite element method-based software package for modeling concrete pavements (ACI 330R-08, 2008).

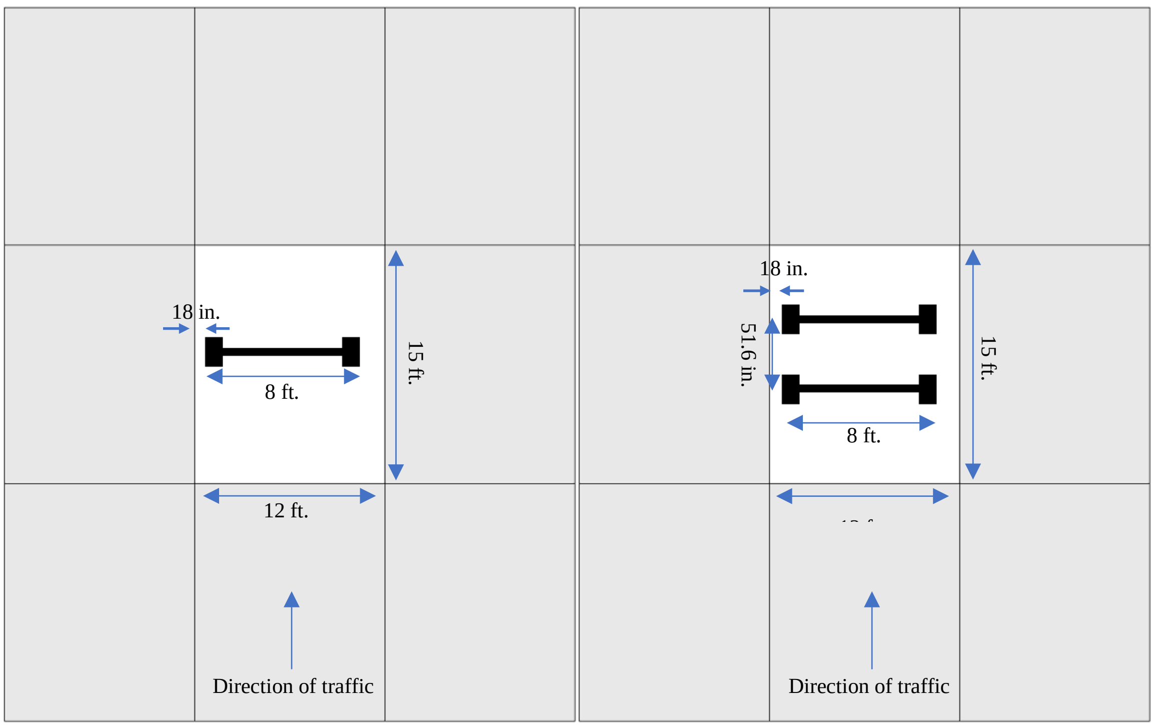
Table 8 Axle load distribution factors for different traffic categories (ACI 330R-08, 2008).

Axle load, kips (kN)	Axles per 1000 truck (Excluding all two-axle, four-tire trucks)			
	Category A	Category B	Category C	Category D
4 (18)	1693.31	1693.31	—	—
6 (27)	732.28	732.28	—	—
8 (36)	483.10	483.10	233.60	—
10 (44)	204.96	204.96	142.70	—
12 (53)	124.00	124.00	116.76	—
14 (62)	56.11	56.11	47.76	—
16 (71)	38.02	38.02	23.88	1000
18 (80)	—	15.81	16.61	—
20 (89)	—	4.23	6.63	—
22 (98)	—	0.96	2.60	—
24 (107)	—	—	1.60	—
26 (116)	—	—	0.07	—
Tandem axles				
4 (18)	31.90	31.90	—	—
8 (36)	85.59	85.59	47.01	—
12 (53)	139.30	139.30	91.15	—
16 (71)	75.02	75.02	59.25	—
20 (89)	57.10	57.10	45.00	—
24 (107)	39.18	39.18	30.74	—
28 (125)	68.48	68.48	44.43	—
32 (142)	69.59	69.59	54.76	2000
36 (160)	—	4.19	38.79	—
40 (178)	—	—	7.76	—
44 (196)	—	—	1.16	—

Description of Finite Element Model Parameters

In a previous research project conducted by the authors, ISLAB2005 models were validated using the data from Lightweight Deflectometer (LWD) tests conducted on 14 existing PC pavements across Washington State. The deflection results from the LWD tests on existing PC slabs agreed with the resulted deflections from modeling the same tested PC slabs by ISLAB2005 (AlShareedah & Nassiri, 2018).

The validated models were then used to simulate single and tandem axle loads as defined in the ACI loading categories discussed above. In doing so, a PC slab was modeled as an interior slab in a cluster of nine slabs (Figure 18). The load transfer mechanism across the joints was defined as aggregate interlocking only because dowel bars are not used in PC pavements. The values used to define all other input parameters for modeling PC slabs subjected to single and tandem axle loads in ISLAB2005 are presented in Table 9.



(a) (b)

Figure 18. Geometry of the modeled PC slab in ISLAB2005: a) single axle, b) tandem axle loading scenarios

Table 9 List of values of slab geometry and axle load-related parameters used in modeling PC pavement in ISLAB2005

Parameter	Assumed value	Reference
Typical slab geometry	12 ft. × 15 ft.	(AASHTOWare, 2015)
Distance from slab edge to wheel location	18 inches	(AASHTOWare, 2015)
Tire pressure	120 psi	(AASHTOWare, 2015)
Typical Average PC density	112 pcf	(ACI 522R-13, 2013)
Aggregate interlocking factor	3,000	(Davids, 2003)
Axle width	8.5 ft.	(AASHTOWare, 2015)
Tandem axle spacing	51.6 inch	(AASHTOWare, 2015)

Three levels of flexural strength were included in the models: 250, 350, and 450 psi, based on the results of laboratory testing obtained in this project, as previously discussed in Section 3. Two typical k-values were included in the models: 100 and 200 psi/in which correspond to the base layer ranging from 12 to 24 inches based on the typical in-situ values reported in previous studies using LWD and falling-weight deflectometer tests (AlShareedah & Nassiri, 2018, Vancura, MacDonald, & Khazanovich., 2011).

These assumptions resulted in a total of six ISLAB2000 models of PC pavements. Each model was then run for each axle load level shown in Table 8 in accordance with the critical axle load arrangement shown in Figure 16. Finally, the applied stress resulted from the ISLAB2005 model for each axle load and the assumed flexural strength of PC was used to calculate the SR and the respective N_f at a 50-percent failure probability (Eq. 4.)

A thickness design database was developed for a 20-year design life and hence, the expected number of load applications (n) was calculated for each axle load using the axle distribution factors in Table 8 and the anticipated average daily truck traffic (ADTT) (Eq. 5.) The ADTT values were selected based on an average traffic data used in the guide (ACI 330R-08, 2008).

$$n = ADTT * axle\ distribution\ factor * 20\ year * 365\ day \qquad \text{Eq. 5}$$

Furthermore, fatigue consumption was defined as the summation of the ratios of n/N_f for all single and tandem axles in each traffic category. The PC pavement thickness was considered adequate for a certain traffic category and material properties, if the total fatigue consumption was less than 125 percent, as specified in ACI 330R-08 (ACI 330R-08, 2008). Allowing the maximum fatigue consumption to exceed 100 percent is justified since the concrete strength continuously increases over time (ACI 330R-08, 2008).

Following the above-mentioned procedure, the recommended design thicknesses for low-traffic-volume PC pavements are presented in Table 10. By selecting a corresponding PC mechanical property, traffic categories, and projected traffic volume, designers can select the PC slab thicknesses from Table 10.

Table 10 Recommended thicknesses for PC pavements with various material properties and under different traffic categories

K-value (psi/inch)		100			200		
M_R (psi)		250	350	450	250	350	450
Category A	ADTT=10	7	6	6	7	6	6
	ADTT=25	7	6	6	7	6	6
Category B	ADTT=25	9	7	6	8	7	6
	ADTT=300	9	7	6	8	7	6
Category C	ADTT=100	10	8	7	9	8	7
	ADTT=300	10	8	7	9	8	7
	ADTT=700	10	8	7	9	8	7
Category D	ADTT=700	9	8	7	9	7	6

The sensitivity of the suggested slab thicknesses to the design life duration was investigated by repeating the same procedure described earlier for 25 and 30 years design lives. The results showed a slight increment in the fatigue consumption, however, the PC thicknesses did not change. It should be noted that the suggested thicknesses need to be updated using a fatigue model which is specifically developed for PC materials.

6. CONCLUSIONS

The mechanical properties of PC produced with different aggregate types, cement contents and porosities were established in this study. PC specimens were cast from different mixture designs and tested for hardened porosity, 28-day compressive and flexural strength. The test results showed that hardened porosity had a significant impact on PC compressive and flexural strength. Further, increasing the cement and water content while keeping the w/c constant did not produce a clear effect on compressive and flexural strength of PC specimens. However, the fresh densities of PC mixtures increased when the cement and water contents were increased. The compressive and flexural strength results were combined with the results from previous similar studies and a regression analysis was carried out to develop relationships between PC strength and mixture design parameters. The proposed multi variable linear regression models can be used to estimate the 28-day compressive and flexural strength of PC using the mixture design variables and the targeted porosity within the range of the input parameters used in this study.

Moreover, this report proposes a recommended thickness design database for low traffic volume PC with different material properties. The proposed thicknesses were developed using a fatigue model that is used in designing conventional concrete pavement. In addition, the traffic categories that are anticipated to occur on PC were adopted from the ACI guide for the design and construction of concrete parking lots. The proposed thickness design table will allow designers to select the required PC pavement thickness based on the expected traffic volume and PC mechanical properties. The thicknesses need to be updated using a fatigue model which is specifically developed for PC materials.

FUTURE RESEARCH

In this report, relationships were presented to predict PC strength from mixture design variables and hardened porosity. The experimental program should be expanded in the future to include PC with various w/c ratios, aggregate types, and cement contents. In addition, the regression models need to be expanded to include more data to improve the accuracy of the predictions. Furthermore, the wide usage of supplementary cementitious materials (SCM) and fibers in concrete require further investigation on the mechanical properties of PC mixed with SCM and fibers. Finally, to achieve a standard procedure for the structural design of PC pavements, a fatigue model for PC is needed.

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