# Preliminary Study to Develop Standard Acceptance Tests for Pervious Concrete

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Somayeh Nassiri
Milena Rangelov
Zhao Chen

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# PRELIMINARY STUDY TO DEVELOP STANDARD ACCEPTANCE TESTS FOR PERVIOUS CONCRETE

by

Somayeh Nassiri, PhD, PEng
Assistant Professor

Milena Rangelov
PhD Candidate

Zhao Chen
PhD Student

**Washington State Transportation Center (TRAC)**
Department of Civil and Environmental Engineering
Washington State University
PO Box 645825
Pullman, Washington

Washington State Department of Transportation
Technical Monitor
Mark Russell, Pavement Engineer

Prepared for

The State of Washington
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Washington State University, PO Box 642910
Pullman, Washington 99164-2910


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16. ABSTRACT: Pervious concrete pavements are permeable pavement systems that are desired for their role in stormwater management and runoff control. Increased popularity in pervious concrete pavement applications has raised the need for the development of quality control and quality-evaluation test procedures that are suitable for pervious concrete compared to traditional concrete. This brief study took a few preliminary steps in this direction by investigating the effect of specimen size on physical properties of pervious concrete such as hardened porosity and density as well as compressive strength ($f'_c$). Moreover, the effect of four different curing regimens with combined air and moist curing over the four-week curing period on the 28-day $f'_c$ for both specimen sizes was investigated. Pervious concrete for this project was sampled from a Washington State Department of Transportation (WSDOT) paving project located on Vashon Island Ferry Terminal. Forty-eight four-inch and 40 six-inch diameter cylinders were cast and tested as part of the study. The results suggested that the four and six-inch diameter cylinders tested in the project demonstrated comparable values of hardened porosity and density, implying that either size specimen is suitable for quality control of such physical properties. Hardened density obtained in the laboratory for cast cylinders was within two percent or less of the fresh density obtained for the mixture in the field, which shows the suitability of the implemented specimen casting and compacting methods. Compressive strength of small cylinders was higher than that of large cylinders by 8-19%, depending on the curing method. The combination of two weeks of air curing and two weeks of moist curing resulted in the highest 28-day $f'_c$ for both specimen sizes. On the other hand, four weeks of air curing yielded the lowest $f'_c$ among the tested specimens. This trend was confirmed by thermogravimetric analysis conducted on cement paste samples from the four curing categories, which showed that moisture curing resulted in leaching of C-S-H and $Ca(OH)_2$ from the paste. The findings of the study need to be expanded in the future to include more mixtures and testing.



17. KEY WORDS
Pervious concrete, porosity, infiltration, compressive strength, curing


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## EXECUTIVE SUMMARY

### Objectives

Long-term trajectory of this research is to develop laboratory and in-field tests for quality control and quality evaluation of pervious concrete. The objective of this brief study was to take the preparatory steps towards this long-term goal by identifying suitable specimen size for testing, proper method of casting and compacting specimens at the job site, compatibility of fresh and hardened physical properties, and finally proper curing method for compressive strength testing.

### Background

Pervious concrete pavements are permeable pavements that provide runoff control while serving as the wearing course for low-traffic volume roads, parking lots, walk/bike pathways and other applications. Recent increases in pervious concrete usage due to its benefits in stormwater management demands a rapid development of standardized acceptance tests suitable for pervious concrete. Currently, only a handful of standardized test procedures is available for pervious concrete, which leads to differences in casting and testing between laboratories and unreliable test results in one laboratory. Therefore, there is a need for considering the intrinsic physical and mechanical properties of pervious concrete and develop test methods that are suitable for pervious concrete compared to traditional concrete.

### Research Activities

The pervious concrete used in the study was obtained during a Washington State Department of Transportation (WSDOT) paving project on Vashon Island Ferry terminal. The fresh pervious concrete was sampled on two paving days. Specimens were cast in the field using pre-determined fresh material weight based on fresh density test of the mixture. A laboratory experiment was then designed to evaluate the effect of specimen size (4-inch versus 6-inch diameter cylinders) on physical properties of hardened porosity and density, and hydraulic properties in terms of infiltration rate. Further, the specimens were subjected to four curing regimes, featuring different combinations of air and moist curing over the four-week period. Hence, the impact of specimen size and curing method on the 28-day compressive strength ($f'_c$) was examined. Finally, the specimens' failure modes during $f'_c$ testing and the respective load-displacement curves were analyzed.

## Conclusions

The experimental results reveal that both cylinder sizes demonstrate comparable values of porosity (~16 percent) and hardened density (~131.5 lb/ft$^3$), as well as a strong linear porosity-density correlation ($R^2$ range: 0.60-0.90). Hardened density established in the laboratory was within two percent of the fresh density established in the field, which indicates that the implemented casting and compaction procedure was suitable for the given mixture design. Four-inch diameter cylinders had higher 28-day $f'_c$ compared to six-inch cylinders by around 8-19 percent, depending on the curing method. Curing regime of two-week air curing and two-week moist curing resulted in the highest 28-day $f'_c$ for both specimen sizes, while four-week air curing had the lowest strength. The results of thermogravimetric analysis (TGA) indicated that moist curing might result in loss of C-S-H and $Ca(OH)_2$ from the cement paste. During $f'_c$ testing, shear failure was the most frequently observed failure type for four-inch cylinders (48 percent of the tested specimens), while 80 percent of the tested six-inch cylinders showed side-fracture failure type. Load-displacement curves of six-inch cylinders indicated that the specimens with side-fracture failure demonstrate higher post-peak strength compared to other failure types.

## INTRODUCTION

Pervious concrete pavement (PCP) is a permeable pavement structure that is used for stormwater management, while serving as the wearing course for sidewalks, parking lots, driveways, and light-traffic roadways. The pavement structure includes a pervious concrete (PC) layer at the top that contains a high amount of purposefully entrapped macroscopic air voids, ranging from 15 to 25 percent of the total volume (Eisenberg et al. 2015). The high air void content allows free drain of water through the layer with infiltration rates ranging 300-2,000 inch/hour (ACI- 522R-10). Currently, a structural layer thickness design procedure is not available for PCP; therefore, the PC layer thickness is selected based on experience, ranging between six and 12 inches in different applications (Figure 1) (ACI- 522R-10). According to Washington Aggregate & Concrete Association (WACA), PC layer thickness ranges 4-5 in for sidewalks/pathways, 5-6 in for residential driveways and light duty parking lots, and 8-10 in for areas with heavier truck traffic (WACA, 2016).

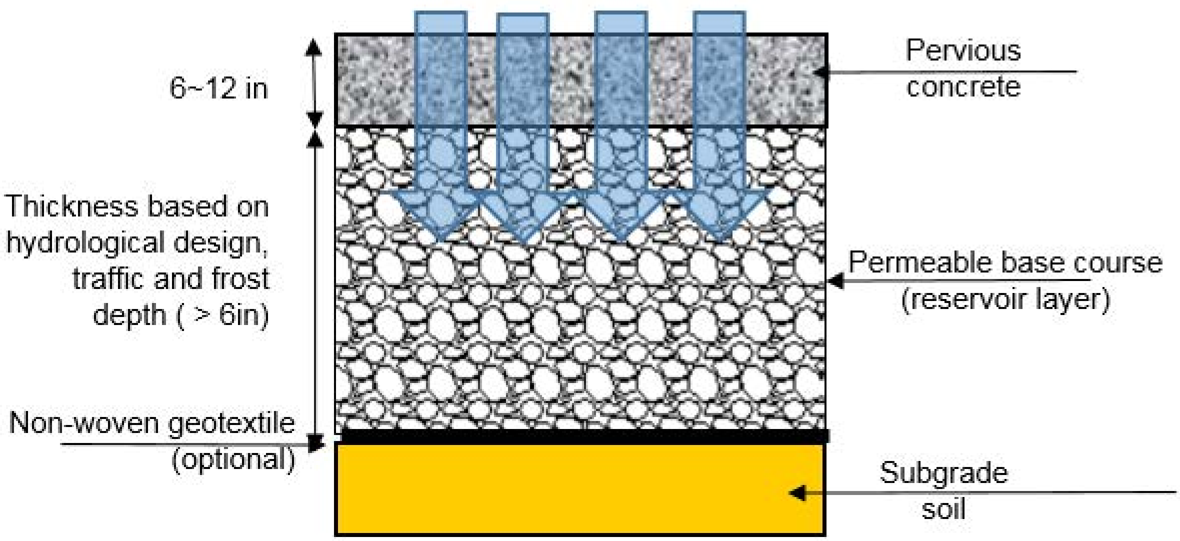



**Figure 1- Typical cross section of a pervious concrete pavement.**

As mentioned earlier, PC's prominent characteristic is the high content of hardened air void achieved by limiting the coarse aggregate grade to a small size ranging ⅜-¾ in with a minimum of 10 percent passing sieve #4 ( CRMCA, 2009). Higher nominal maximum sizes of coarse aggregate may yield in higher porosity, however at the detriment of workability and mechanical properties ( CRMCA, 2009). Fine aggregate is either completely removed from the mixture or is included in a limited amount of 6 ± 2 percent for additional strength and freeze-thaw durability (Kevern *et al.*, 2008; CRMCA, 2009). The end result is a matrix of coarse aggregate (that is) interconnected by bridging layers of paste as opposed to conventional portland cement concrete (PCC), where the aggregate is fully embedded in the paste. Naturally, such voided structure results in lower mechanical properties also associated with high variability, depending on the method of placement/casting and compaction.

The PC layer is placed on a permeable, open-graded, and clean stone base layer commonly ASTM No. 2, 3, or 57 river rock or crushed stone, depending on local availability (CRMCA, 2009). The thickness of the base layer depends on the traffic volume and loads, local environmental parameters such as precipitation, evaporation, subgrade soil's infiltration rates, intended stormwater functionality (detention or the recharge), and hydrological design. The minimum recommended thickness for the base layer that serves as a stormwater storage is six inches (CRMCA, 2009). Most likely, this thickness needs to be increased in cold regions with freeze-thaw cycling. In the absence of a structural pavement design procedure for PCP layers, ACI 330R-13 "Guide for the Design and Construction of Concrete Parking Lots" is suggested to be consulted (ACI. 522R-13).

With regular maintenance to avoid clogging, PCP allows for drain down of runoff and reduces pooling and ponding of rain and snowmelt water, which is especially desired in areas with high rain volume. Other environmental benefits may include reduction of the heat-island effect in urban areas and noise mitigation (Haselbach *et al.*, 2011; Kevern *et al.*, 2012). These advantages have made PCP appealing for such applications as parking lots, sidewalks, driveways, bike lanes, walking paths and light-traffic roadways and has made PCP a stormwater management tool for low-impact development (LID) projects across Washington state (WACA, 2016).

Despite the challenges and the lack of standardized test procedures, PCP's advantages in stormwater management have led to increased usage. As a result, there is a demand for the fast development of acceptance specifications for PC. Currently, only a handful of standardized test procedures are available for testing PC's fresh and hardened properties. Table 1 presents the standardized procedures available today to determine PC's different properties. Furthermore, Table 1 also encompasses the procedures for PC testing that are under development. As shown in the table, the American Concrete Institute (ACI- 522R-10)'s 522 Committee's document:

“Specification for Pervious Concrete Pavement ACI 522.1-13” (ACI. 522R-13) is currently the only comprehensive document on properties of PC, which includes recommendations for materials, preparation, and placement of PC. However, this publication was last visited by the committee in 2013, and due to the fast growth and development of PCP is outdated and requires updating (this document is being currently updated by the committee). The standardized test methods from the American Society for Testing and Materials (ASTM) represents the most extensive framework in PC testing. Available ASTM test methods are the determination of fresh density, hardened density and porosity, and infiltration rate: ASTM C1688, ASTM C1754, and ASTM C1701, respectively. Standardized procedure ISO 177851: 2016. Testing Methods for Pervious Concrete-Part 1: Infiltration Rate also outlines the procedure for the characterization of PC infiltration rate (ISO 177851-1:2016).

**Table 1- List of available guidelines and standardized test procedures for PC evaluation.**

| Standard Designation | Standard full name | Property of PC |
|---|---|---|
| ACI 522.1-13 | Specification for Pervious Concrete Pavement (under revision) | Materials, preparation, forming, placing, finishing, jointing, curing, and quality control of pervious concrete pavement |
| ASTM C1688 | Standard Test Method for Density and Void Content of Freshly Mixed Concrete | Fresh density and porosity |
| ASTM C1701 | Standard Test Method for Infiltration Rate of In Place Pervious Concrete | Infiltration rate |
| ASTM C1747 | Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion | Percentage mass loss after 500 cycles in L.A. abrasion rotating steel drum |
| ASTM C1754 | Standard Test Method for Density and Void Content of Hardened Pervious Concrete | Porosity and hardened density |
| ASTM C1781 | Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems | Infiltration rate |
| ASTM C944 | Standard Test Method for Abrasion Resistance of Mortar Surfaces by The Rotating Cutter Method | Percentage mass loss after three 2-min periods of the abrasion treatment |
| ISO 17785-1: 2016 | Testing Methods for Pervious Concrete -- Part 1: Infiltration Rate | Infiltration rate |
| ISO 17785-1: 2016 (under development) | Testing Methods for Pervious Concrete -- Part 2: Hardened Density | Porosity and hardened density |

In terms of mechanical properties, standardized procedures are not available for casting and curing PC specimens, neither exists mechanical testing procedures that would result in reliable and meaningful test results within tolerable test variations. As a result, the procedures available for conventional PCC are typically modified for PC testing in the absence of more appropriate methodologies. Consequently, a variety of methods has been used to cast specimens and conduct mechanical testing, often yielding in unreliable and incomparable results. In terms of durability tests, the procedure specified in ASTM 1747 provides an estimate of PC potential resistance to degradation by impact and abrasion. Further, the rotating cutter method was used to evaluate the abrasion resistance of PC as per ASTM C944 & (Dong *et al.*, 2012).

The overall objective of this research was to conduct a series of tests to identify those that can be used for acceptance of PC mixtures and PCP placements in the field and in the laboratory. The specific focus of this study was to evaluate the reliability of the results of 28-day compressive strength ($f'_c$) as well as fresh and hardened density, porosity, and infiltration rate. As part of the investigation, the effect of cylindrical specimen size on $f'_c$, and hardened density was also evaluated. Furthermore, the effect of air- versus moist curing method, as well as curing duration on 28-day $f'_c$ was investigated.

## REVIEW OF CURRENT TESTS OF PERVIOUS CONCRETE

### Fresh density and hardened density

Fresh density and hardened porosity are the most common acceptance tests for quality evaluation of PC. The fresh density of PC is determined based on ASTM 1688. In this procedure, fresh PC mixture is placed in the standard container with known weight and volume in two approximately equal lifts. Each lift is then compacted with 20 blows of the standard 5.5-lb Proctor Hammer with a 12-in drop. After the second lift is compacted, the top is finished flat using a strike-off plate and the weight of the container with fresh PC is recorded. The fresh density of PC is calculated as the ratio of the mass of fresh PC by the volume of the container.

Hardened density is determined following ASTM C1754 that is typically performed on seven-day-old specimens. In this procedure, hardened density is calculated by dividing the dry mass by the volume of the specimen. The dry weight of the specimens is first recorded ($M_d$) and then the dimensions of the specimens (height and diameter) are recorded to obtain the volume (V). To do so, two caliper measurements are taken at mid-depth to obtain the diameter, followed by two height measurements. Hardened density is calculated as the ratio of the dry mass to the volume of the specimen ($M_d$/V). To characterize porosity, each specimen is submerged in water for at least 30 minutes, after which the submerged mass of each specimen is recorded ($M_W$). The volume of the solids is obtained by dividing the difference between the dry and submerged weights by the density of water ($\rho_w$). Subsequently, porosity ($\phi$) is calculated using Eq. 2:

$$\varphi = 1 - \frac{(M_d - M_w)}{\rho_w * V} \tag{2}$$

The size of the specimen may affect the hardened density and the ease of achieving the target density. Pervious concrete- similar to conventional PCC- is placed and compacted in two and three lifts, when casting 4-in and 6-in diameter cylinders, respectively. To achieve the target density as per the mixture design, and a uniform density throughout the specimen's height, each lift needs to be pre-weighed and placed in the mold to fit the required volume. Depending on workability, the mixture is placed to fit the mold, either through compaction by certain drops of the Proctor hammer or by strikes of a rubber mallet or a combination of both methods. With the varying number of lifts between the two cylinder sizes, it is critical to make sure that both specimen sizes yield reliable results in terms of density for acceptance evaluation. An empirical relationship can be developed to correlate the hardened density of the two size cylinders.

**Infiltration rate**

As described earlier, PC's matrix contains an interconnected system of air voids that allows the drain down of runoff. This characteristic of PC is desirable for stormwater management; therefore, it is important to test and establish the rate of infiltration for PC. Fortunately, an ASTM procedure exists for infiltration rate evaluation. The procedure for the determination of the infiltration rate of in-place PC is available in ASTM C1701. A watertight infiltration ring with a 12-in diameter is fixed on the surface of the PCP using plumber's putty. The time that takes for the known mass of water to infiltrate through the ring is measured. The test is repeated at multiple locations on the PCP surface. Infiltration test at each location is preceded by pre-wetting of the PCP with eight pounds of water. Each test should be performed within two minutes after the completion of the pre-wetting. The number of test locations is determined based on the area of the pavement. Three test locations are recommended for the pavement areas up to 25,000 $ft^2$, while an additional test location should be added for every extra 10,000 $ft^2$. A minimum three feet of clear distance between the test locations should be allowed. Tests should not be performed within 24 hours of the last precipitation event. Infiltration rate of in-place PCP in in/h is calculated based on Eq. 3:

$$I = \frac{KM}{D^2 t} \quad (3)$$

where, M is the mass of infiltrated water in lbs, D is the inside diameter of the infiltration ring in inches, t is the time required for the designated mass of water to infiltrate through PC in seconds, and K is the correction factor equal to 126,870 inches.

This type of infiltration test is suitable for the in-field PCP. Infiltration rate of cylindrical PC specimens is determined in the laboratory based on a modified version of ASTM C1701. After the hardened porosity and density tests are completed on the specimens, specimens are wrapped on the sides with shrink-wrap, which enables the vertical flow of water without any loss from the sides, as shown in Figure 2. Similar to ASTM C1701 procedure, the test is based on the measurement of the time required for the known volume of water to flow through the specimen. Infiltration rate is calculated based on the Eq. 4:

$$I = \frac{4V}{D^2 \pi t} \quad (4)$$

where, V is the volume of the infiltrated water, D is the diameter of the specimen, and t is the time required for the designated volume of water to infiltrate through PC. Infiltration test is conducted with one and two liters of water for 4- and 6-in cylinders, respectively. Each infiltration tests is preceded with pre-wetting of the specimen with the same amount of water used in the test. The infiltration is reported as the average of the two consecutive measurements.

**Figure 2- Infiltration test setup.**

**Compressive strength ($f'_c$)**

The most common quality assurance test for traditional PCC is the 28-day $f'_c$ test, which is conducted on cylindrical specimens that are cast at the job site and cured for later testing of hardened properties. In the lack of a mechanical test procedure appropriate for PC, ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," is followed for PC testing. Load rate of 35 ± 5 psi defined for traditional PCC needs to be adjusted to compensate for the lower $f'_c$ of PC to provide for a reasonable test duration per specimen and a steady no shock loading during the test. Furthermore, the details regarding specimen preparation, curing, capping, as well as the failure types specified in ASTM C39 do not correspond to PC and require modification.

One of the aims of this study was to evaluate the reliability of using 28-day $f'_c$ as a QA/QC test for PC. In doing so, specimens need to be cast at the job site or in the laboratory in the proper size. ASTM C39 requires $f'_c$ test to be conducted on 6 in diameter by 12 in height cylinders. However, 4 by 8 in cylindrical specimens are more desirable for several reasons. They are cast faster as they require a smaller number of lifts and compactions, they weigh less (approximately 7.5 lb for a typical 4-in, as opposed to 25 lb for a 6-in cylinder for a typical PC density of 130 lbs/ft$^3$), and consequently are easier to transport, store and cure. Therefore, there is merit in investigating whether 4-in cylinders can be used for QA testing of PC instead of 6-in cylinders. Research studies conducted on conventional PCC show that generally a linear relationship exists between $f'_c$ of 4-in cylinders ($f_{c-4}$) and that of 6-in cylinders ($f_{c-6}$):

$$f_{c-4} = k_s \times f_{c-6} \quad (1)$$

Experimentally determined values of $k_s$ from the literature range from 0.68 to 1.19, with $k_s$ being greater than unity for PCC strengths below 6,000 psi (Vandegrift and Schindler, 2006), which is the case for pervious concrete mixtures. This relation needs to be investigated to establish a proper value for $k_s$ for pervious concrete.

While not as commonly used, 28-day $f'_c$ test may still be conducted as an acceptance test for pervious concrete and to provide insight into mechanical properties of the mixture. However, $f'_c$ results conducted on the two size cylinders inherently vary, and therefore it is important to ensure that 4-in cylinders still provide reliable test results for acceptance evaluation.

In addition to cylinder size, another factor that can substantially affect $f'_c$ results is the curing methodology and curing duration. As opposed to conventional PCC, pervious concrete requires a longer wait before demolding to avoid dislodging of aggregate and breakage of the matrix during demolding, handling and transporting. Commonly, a seven-day period is allowed before demolding the specimens. The same period is typically used before PCPs are opened to traffic. During the in-mold seven-day curing, the specimens for acceptance testing are cured either in the field or in the laboratory's ambient conditions or in a combination of both. No standardized procedure exists for curing the specimens upon demolding. As such, normally specimens are continued to air cure until the designated testing day. The effect and significance of moist curing in the development of strength in conventional PCC are well known (Aitcin *et al.*, 1994). However, our past exploratory experiment revealed that placing PC specimens in lime-saturated water bath upon demolding might result in the dissolving of the paste matrix, and a reduction in 28-day $f'_c$ of between five to 27 percent when compared to air-cured specimens. Therefore, this topic deserves further investigation before standard procedures can be developed for 28-day $f'_c$ acceptance testing of PC.

## PROJECT OVERVIEW

### Field work

Specimens tested in this study were cast from the Washington State Department of Transportation (WSDOT) 's PCP placement on Vashon Ferry Terminal's dock on two paving days, June 1 and 17 2016. Construction took place at Vashon Ferry Terminal at Vashon Island, WA (Figure 3).

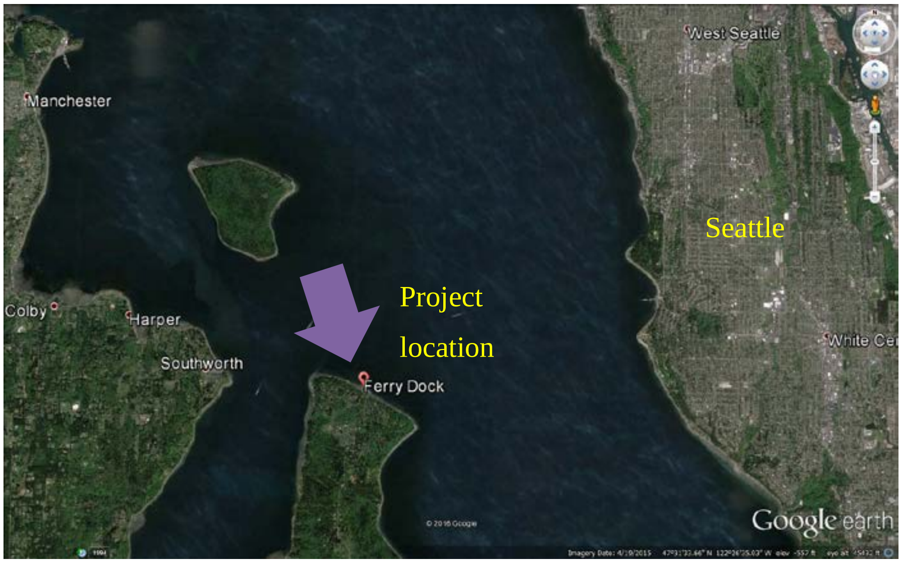



**Figure 3- Project location with respect to Seattle, 47°31'33.66'' N and 122°26'35.03''W. Google Earth. June 3, 2016 (available from: https://www.google.com/maps/).**

Pervious concrete was placed in four lanes (Figures 4); the lanes were paved seven days apart from one another. The sequencing allowed for proper curing period, opening the paved lane to traffic, and closing the adjacent lane for concrete placement. WSU research team was present at the paving site for testing and collecting specimens on two paving days as mentioned above. The two northbound lanes were placed June 1st 2016 (Figures 4-6). On June 17th 2016, the outer southbound lane was placed. The dock was fully paved and opened to traffic by August 2016.


**Figure 4- Vashon Ferry Terminal Construction Lanes (WSDOT, 2016).**

**Figure 5- Northbound lanes under construction on June 1 2016.**

**Figure 6- Southbound lane under construction on June 17 2016.**

### Pervious concrete placement

In preparation for the placement of the six-inch deep PC layer, two by six-inch timber was used as molds, placed along the lane boundaries in advance of paving. A geotextile membrane was spread on the dock to separate the PC from the dock, for easy removal, if needed.

A total of seven and eight concrete trucks delivered and placed the fresh PC on site on June 1 and 17, respectively. Pervious concrete was deposited from the mixer truck's chute within the formwork and was spread to position manually using floats. A vibratory roller screed, weighted by water fill, was supported at two sides by the formwork and was rolled on the surface of the PC to provide a flat finish (shown in Figure 7-a). A hand-held steel roller was then passed on the finished surface to compact the concrete slab (Figure 7-b); a similar roller with a cutting plate at middle was used to cut the joints (Figure 7-c).

Transverse joints were immediately cut in plastic pervious concrete at 15-feet spacing, up to the bend at the northern end, where the joint spacing was decreased to 11.5 ft. After placement, finishing and compacting, polyethylene sheets were placed atop the freshly placed slabs to cover the slabs and allow curing for seven days (Figure 7-d). Figure 7-e is a photo of the hardened PC pavement in the outer lane after the curing period.


**Figure 7- (a) Finishing PC flat using a vibratory roller. (b) Roller compacting PC. (c) Joints cutting. (d) Freshly placed PCP covered with plastic sheets for curing. (e) Hardened PCP in the outer lane after the curing period.**

### Materials and mixture design

Mixture design and proportioning of the PC constituents are provided in Table 2. The coarse aggregate nominal maximum size was 3/8 in, with a specific gravity of 2.733. Maximum allowed mixture water was defined as 140 lb/yd$^3$ in the mixture design, the actual mixture water varied between 46 and 72 lb/yd$^3$, based on the batch slips collected on the paving days from the concrete trucks. The mixture's density was 130.99 lb/yd$^3$ according to the mixture design, resulting in a target porosity at 20.4 percent. Hydration stabilizer admixture, Recover, and rheology-modifying admixture, V-Mar 3, from W.R. Grace & Co. were added to the mixture in dosages specified in Table 2. The purpose of admixtures is to delay the PC setting and provide prolonged workable time, per the manufacturer's datasheet ( Grace Concrete Products, 2013).

**Table 2- PC mixture design and proportioning.**

<table>
<tr><th colspan="2">Material</th><th>Amount per yd³ of PC</th></tr>
<tr><td colspan="2">Coarse Aggregate [lb]</td><td>2,893</td></tr>
<tr><td colspan="2">Fine Aggregate [lb]</td><td>0.0</td></tr>
<tr><td colspan="2">Type I/II Cement [lb]</td><td>505</td></tr>
<tr><td colspan="2">Water [lb]</td><td>46.4~71.4</td></tr>
<tr><td rowspan="2">Admixtures</td><td>Recover from Grace [oz]</td><td>33</td></tr>
<tr><td>V-Mar from Grace [oz]</td><td>34</td></tr>
</table>

### Fresh PC testing and sampling

Nine wheelbarrow-full of the fresh PC were sampled from multiple trucks on the two paving days. Fresh density was determined for each batch based on ASTM 1688. Fresh PC mixture was placed into the standard bucket in two equal lifts, both of which were compacted with 20 blows of the standard 5.5-lb Proctor Hammer with a 12-in drop, as shown in Figure 8-left. When the second layer was compacted, the top was finished by the strike-off bar, as illustrated in Figure 8-right, and the weight of the fresh PC was recorded. The fresh density of PC was determined as the ratio of fresh PC mass to the known the volume of the bucket.

**Figure 8- ASTM 1688 fresh density test: (left) compaction of PC by the standard Proctor Hammer, (right) finishing the fresh PC flat with a strike-off bar.**

The remaining mixture was used to cast 4- and 6-in cylinders. The required mass of fresh material placed in every mold was defined based on the experimentally determined fresh density on the same batch, as described above. The material was divided in two and three equal lifts for 4- and 6-in cylinders, respectively. Fresh PC was compacted using a standard Proctor Hammer, as presented in Figure 9-left. The number of hammer drops was adjusted so that the predetermined mass of the fresh PC fit in the molds. Additionally, strikes of the rubber mallet were applied as needed to facilitate casting and avoid segregation (Figure 9- right). A total of 48, 4-in and 40 6-in cylinders were cast on the two paving days.

**Figure 9- Compacting PC into cylindrical specimens: (left) by the Proctor Hammer, (right) additional strikes of the mallet to avoid undesired pockets of air.**

## Curing and testing

After casting, the specimens were field-cured for a duration between one and three days according to ASTM C31, then transported to WSU's concrete material characterization laboratory (CMCL) and cured in closed molds in laboratory condition at 73˚F for seven days. Upon demolding at 7-day age, hardened density and porosity of each specimen were determined based on the procedure in ASTM C1754. Infiltration rate was determined for the each specimen based on ASTM C1701, after the porosity and hardened density tests.

Later, the specimens were cured until 28 days of age. In order to assess the impact of different curing methods on strength development, the specimens were cured in air and in a concrete curing fog room complying with ASTM C192. The duration of air and moist curing was designed to include four curing categories, as described in Table 3. The four categories are four weeks of air curing (4A), three weeks in air and one week moist cured in the fog room (3A1M), two weeks of air and two weeks of moist curing (2A2M), and finally one week of curing in air, followed by three weeks of moist curing (1A3M). Table 3 also shows the number of cylinders of both sizes designated to each curing category. Note that the unequal number of specimens in each curing category is the result of a different number of cylinders cast on the two paving days. Regardless, a sufficient number of specimens are included in each category to allow for meaningful statistical comparisons. After 28 days (four weeks) of curing, specimens were tested for the compressive strength.

**Table 3- Four curing methodologies for PC with the corresponding sample sizes.**

| Label | Description of Curing Method | #Cylinders | |
|---|---|---|---|
| | | 4-in Dia. | 6-in Dia. |
| 4A | 4 weeks cured in air | 16 | 11 |
| 3A1M | 3 week cured in air, 1 weeks moist cured | 12 | 11 |
| 2A2M | 2 weeks cured in air, 2 weeks moist cured | 10 | 10 |
| 1A3M | 1 weeks cured in air, 3 weeks moist cured | 10 | 8 |

Compressive strength tests were conducted based on the procedure in ASTM C39, with a modification in loading rate. The specified loading rate of 35 ± 7 psi/s, recommended for conventional PCC results in failure of the specimens in less than two minutes. Therefore, the loading rate was reduced to 15 ± 3 psi/s to allow for the test on each specimen to last for about four to five minutes. Specimens were capped with the unbounded metal caps with neoprene pads to ensure the uniform loading over the cross-sectional area. During the compressive strength testing, the failure mode of the each tested specimen was recorded and categorized based on the recommendations outlined in ASTM C39. Moreover, load-displacement charts were recorded for 12 of the tested 6-in cylinders. Figure 10 presents the $f'_c$ test experimental setup.

**Figure 10- Compressive strength test experimental setup.**

## TEST RESULTS & DISCUSSIONS

### Hardened porosity & density

As mentioned earlier, porosity (ϕ) and hardened density (ρ) tests were performed on PC specimens upon demolding on 7-day age. The average ϕ and ρ, with the corresponding standard deviations, represented by whisker bars, are provided in Figure 11. It is noteworthy that one 6-in specimen was removed from the data due to a high porosity of 25 percent, which is outside the range targeted in this study. As seen in Figure 11, the two cylinder sizes present comparable values of average ϕ, at approximately 16 percent. Porosity ranged 10.2-21.0 percent for 4-in and 10.0-21.6 percent for 6-in cylinders. Standard deviations show that the 6-in cylinders had slightly lower variations in both ϕ and ρ, comparing to 4-in cylinders. In terms of ρ, both cylinders demonstrate relatively consistent and comparable values of approximately 131.5 lb/ft$^3$, which corresponds well with the design density at 130.99 lb/ft$^3$.

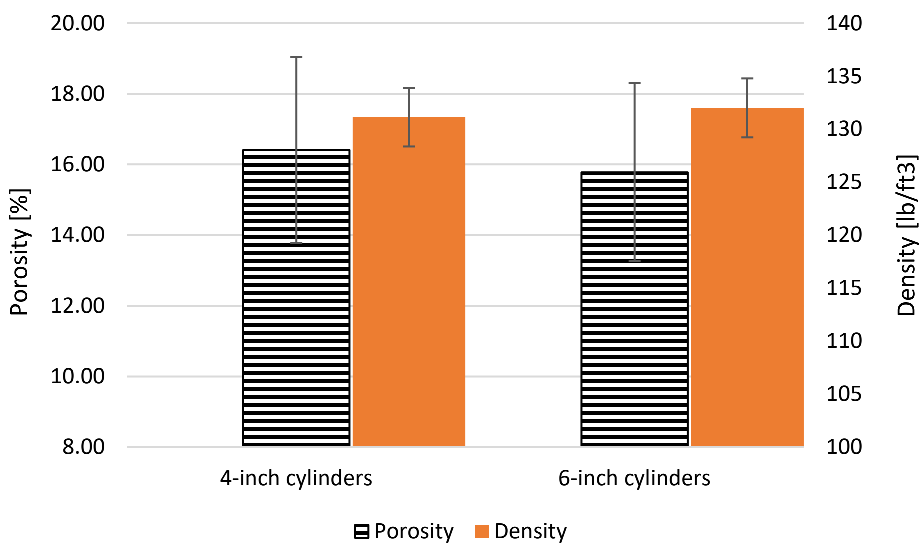



**Figure 11- Porosity ($\varphi$) and hardened density ($\rho$) for both cylinder sizes.**

The linear relationship between ρ of 4- and 6-in cylinders, analogous to the one presented in Eq. 1 is formulated in Eq. 4:

$$\rho_4 = 0.993 \times \rho_6 \quad (4)$$

where, $\rho_4$ and $\rho_6$ stand for hardened densities of 4- and 6-in cylinders, respectively. As seen in Eq. 3, the correlation coefficient is close to unity. Therefore, for practical purposes, for the specimens tested in this study, it is safe to assume that either size specimen can be used for density evaluation. To further make sure that the results for $\rho_4$ and $\rho_6$ are statistically equal, a Pearson t-test at 95 percent confidence interval was performed on porosity and hardened density, and the results are listed in Table 4. As seen in Table 4, relatively high p-values indicate that there is no statistically significant difference neither in ϕ nor in ρ between the two cylinder sizes.

**Table 4- Average porosity (φ), hardened density (ρ) and the results of Pearson t-test for comparison of φ and ρ 4-in vs. 6-in cylinders**

| Property | Mean | Standard Deviation (STDV) | p-value |
|---|---|---|---|
| $\phi_4$ [%] | 16.4 | 2.63 | 0.261 |
| $\phi_6$ [%] | 15.8 | 2.52 | |
| $\rho_4$ [lb/ft$^3$] | 131.1 | 2.77 | 0.150 |
| $\rho_6$ [lb/ft$^3$] | 132.0 | 2.78 | |

Figure 12 presents the correlation between porosity and hardened density for 4- and 6-in cylinders. As Figure 12 indicates, strong linear φ-ρ correlations exist for both cylinder sizes. As expected, specimens with higher values of φ demonstrate higher ρ. It can be observed from Figure 12 that 6-in cylinders present a stronger φ-ρ correlation ($R^2$~0.9), compared to 4-in cylinders ($R^2$~0.6). This difference might be correlated to the more variation in porosity in 4-in cylinders, as discussed earlier in Table 4. The results of Pearson correlation test between φ and ρ reveals a statistically significant correlation (p-values = 0.000) with correlation coefficients -0.776 and -0.947 for 4- and 6-in cylinders, respectively.

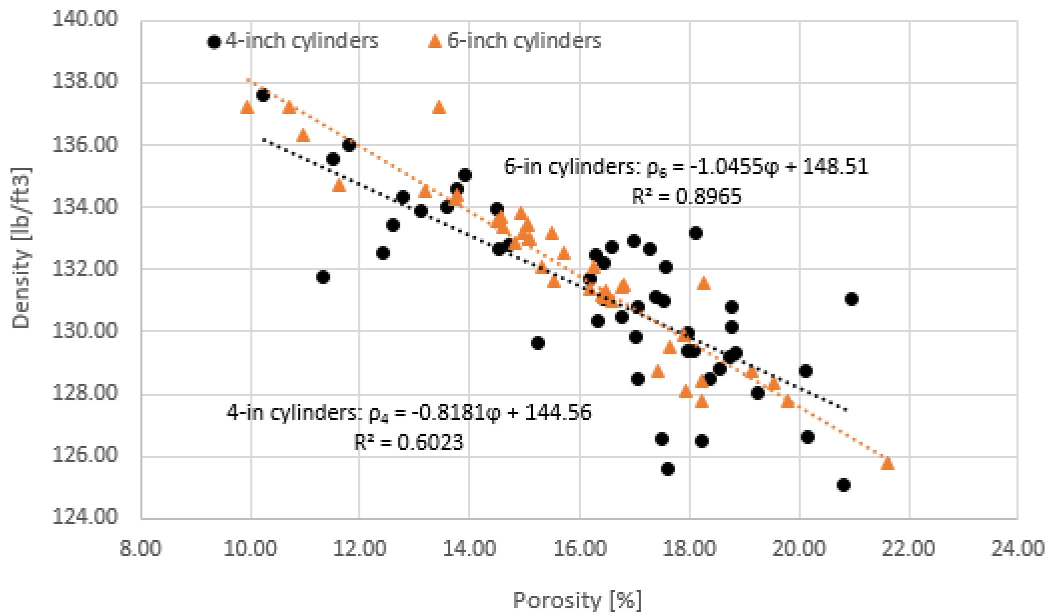



**Figure 12- Linear φ-ρ relationship for 4- and 6-in cylinders.**

The fresh density of PC (D), determined in the field based on ASTM C1688, is commonly used as a quality control tool (NRMCA, 2016). Density from the tests conducted in the field is compared to hardened density (ρ) determined in the laboratory, to evaluate the casting and compaction procedure (

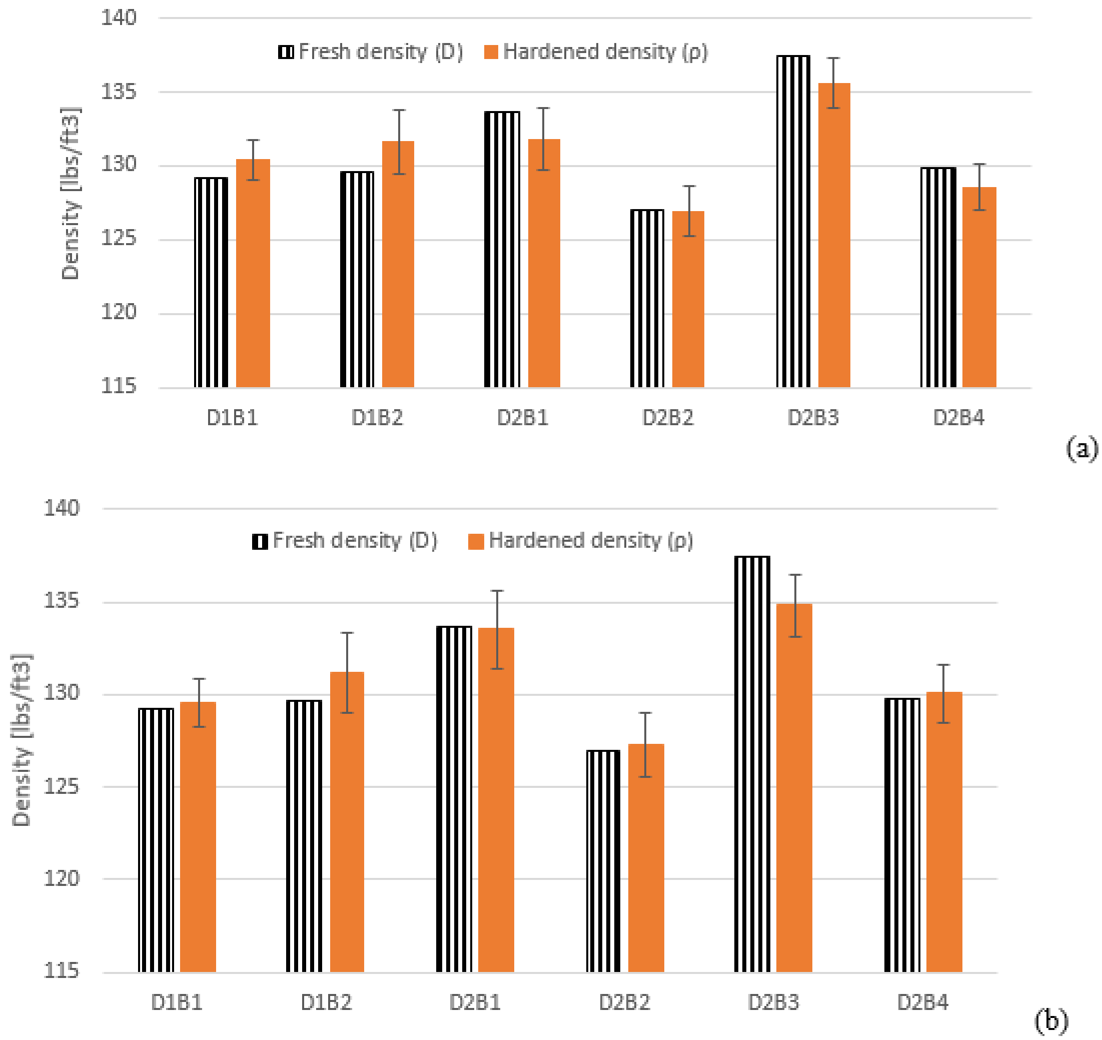
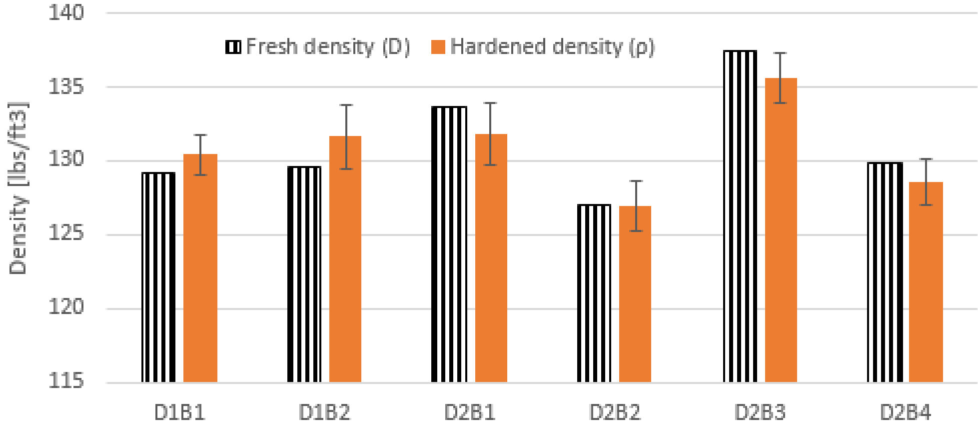
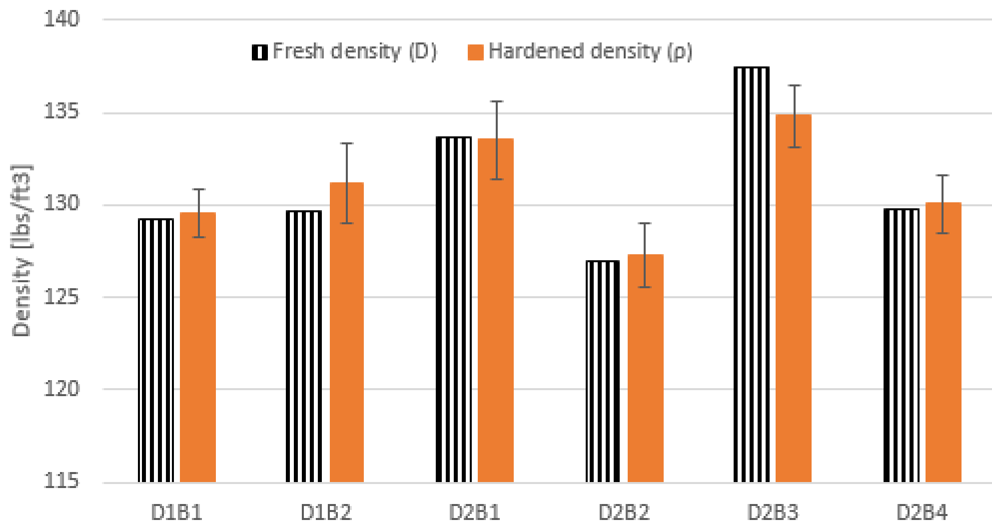



Figure 13). As seen in

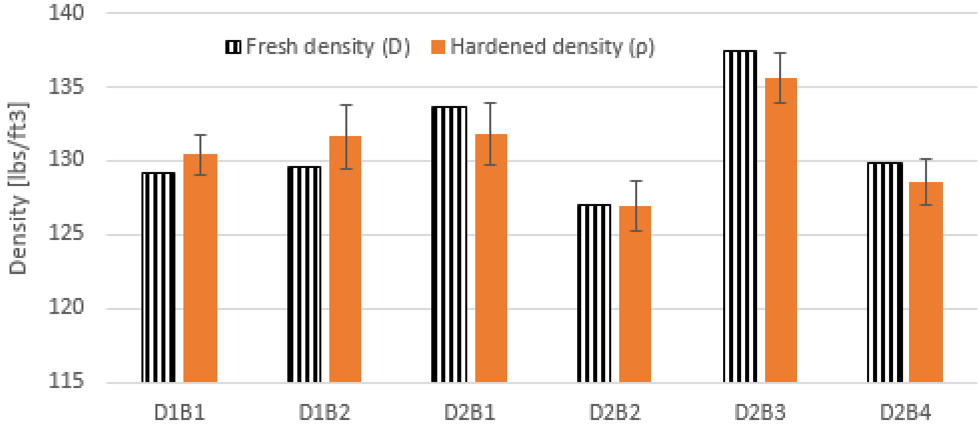



(a)

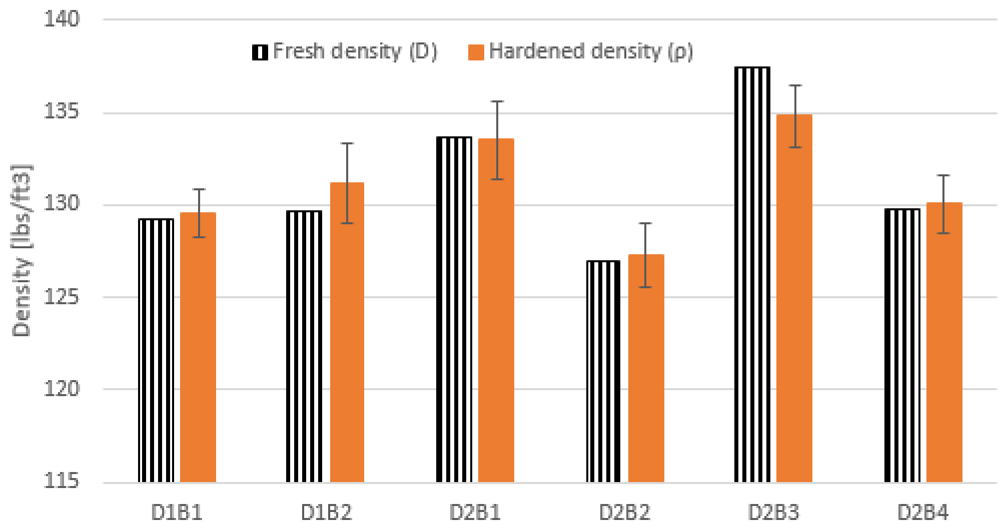



(b)

Figure 13, ρ agrees closely with the D determined in the field, for both cylinder sizes. Percent difference between D and ρ ranges from 0.05 to 1.5 percent for 4-in and from 0.1 to 1.9 percent for 6-in cylinders. The close agreement between the D and ρ indicates that the method of casting specimens based on the predetermined weight and implemented compaction methodology provided a suitable framework for casting PC cylinders in the field. Furthermore, the results presented in




(a)




(b)

Figure 13 demonstrate that for the specimens tested in this study, both cylinder sizes can be used for quality control of the PC used in the field.

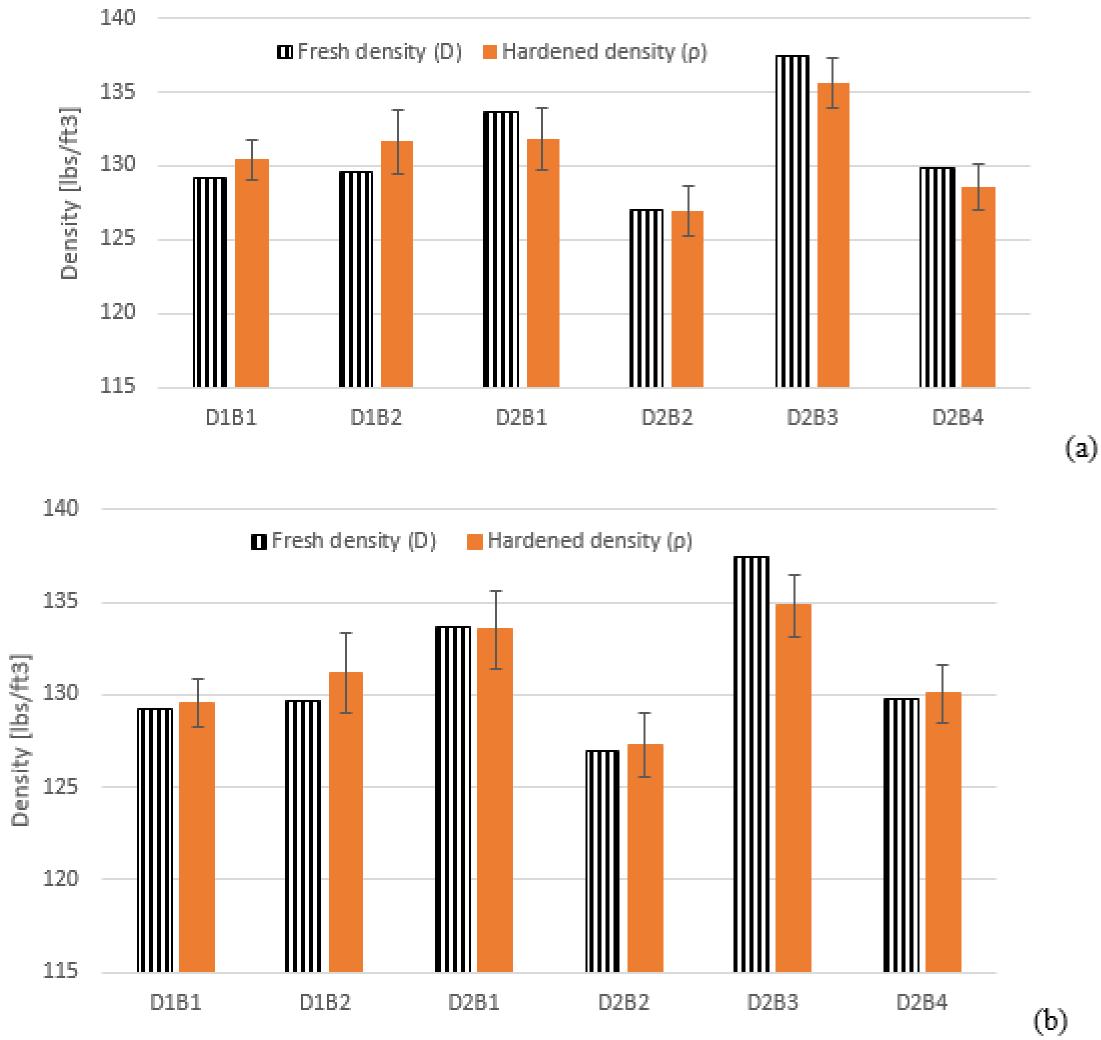



**Figure 13- Comparison of fresh (*D*) and hardened density (*ρ*), based on casting day 1 or 2 (D1 or D2) and PC sampling batch (B1~B4) for (a) 4-in and (b) 6-in cylinders.**

## Infiltration rate

Porosity and hardened density tests were followed by infiltration tests performed on all cast cylinders. The average infiltration rates, with the corresponding values of standard deviations, are presented in Figure 14. The average infiltration rates are 804 and 689 in/h, for 4- and 6-in cylinders respectively. Six-inch cylinders are characterized with lower and more uniform infiltration rates (lower standard deviation) comparing to 4-in cylinders, as Figure 14 indicates. More consistent infiltration rates of 6-in cylinders correspond to more consistent values of porosity and hardened density. It is worth mentioning that the infiltrations of both specimen sizes are within the typical range for PC, which is from 300 to 2,000 in/h (ACI- 522R-10).

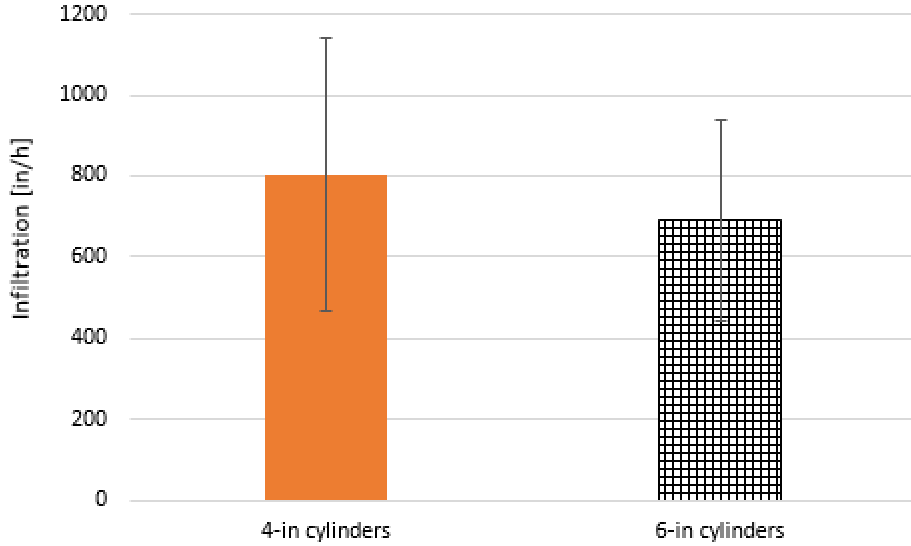



**Figure 14- Average infiltration for 4- and 6-in cylinders.**

Figure 15 presents the infiltration rates of all tested cylinders versus their corresponding porosities. As seen in Figure 15, the specimens characterized with higher porosity generally present higher infiltration, as expected. However, for 4-in cylinders, the values of infiltration are more scattered comparing to 6-in cylinders.

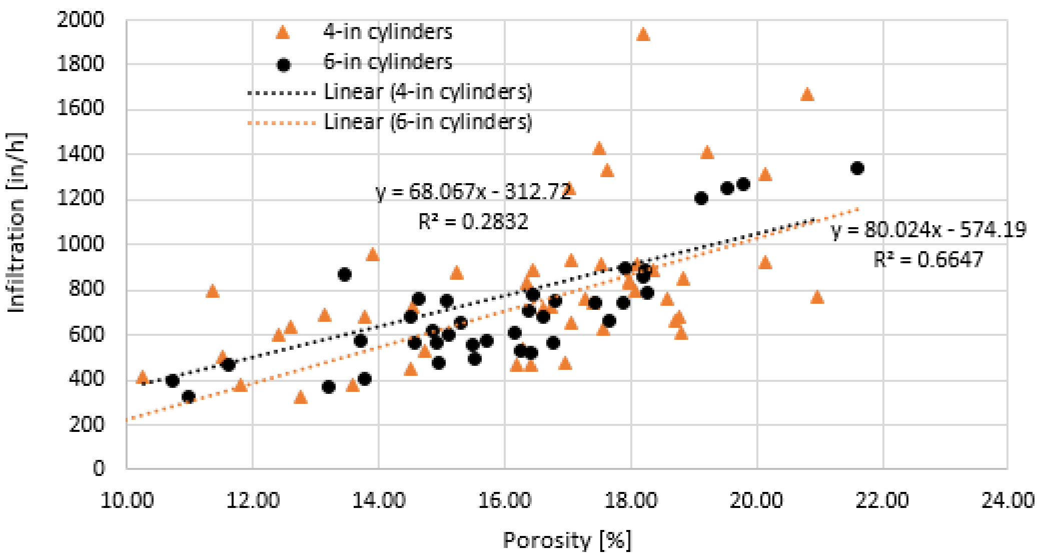



**Figure 15- Infiltration versus porosity for 4- and 6-in cylinders.**

## Compressive strength- effect of specimen size

Compressive strength tests were performed on PC specimens at the 28-day age on all specimens in the four curing categories. Average $f'_c$ with corresponding standard deviations, for the two specimen sizes and four curing categories, are provided in Figure 16. The average 28-day $f'_c$ for 4- and 6-in cylinders from all curing categories are 2548 and 2899 psi, respectively. Both values of $f'_c$ are within the typical range for previous concrete, 500~4000 psi (Tennis *et al.*, 2004). As seen in Figure 16, 4-in cylinders generally present higher values of $f'_c$, by 7.7 to 19 percent, and lower standard deviations, comparing to 6-in cylinders, across all curing categories.

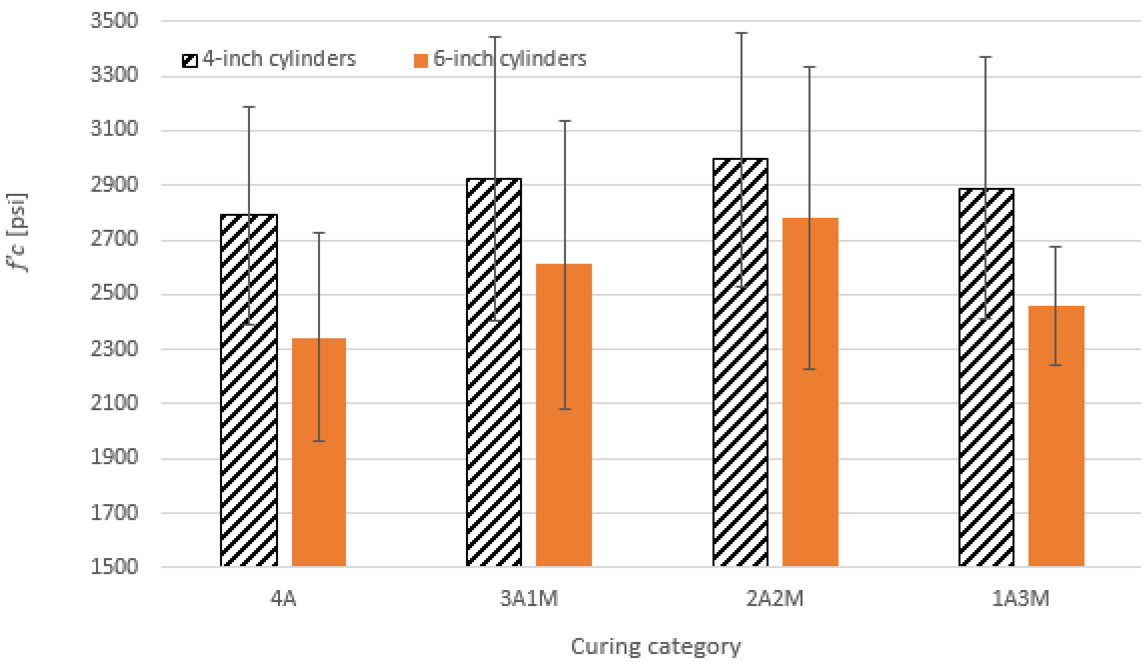



**Figure 16- Average 28-day $f'_c$ for 4- and 6-in PC cylinders for four curing categories.**

Pearson statistical t-test was conducted, aiming to determine whether the impact of cylinder size on $f'_c$ is statistically significant. P-values, provided in Table 5, indicate that $f'_{c-4}$ and $f'_{c-6}$ differ significantly for curing categories 4A and 1A3M. The difference between $f'_c$ for cylinders from 3A1M and 2A2M is not statistically significant, based on the results listed in Table 5. When $f'_c$ all cylinders, regardless of the curing category, were compared, the p-value was 0.002, indicating a significant difference between $f'_c$ for the two cylinders.

**Table 5- Significance of effect of cylinder size on 28-day $f'_c$ based on Pearson t-test**

| Curing category | Specimen size | Mean (psi) | STDV (psi) | p- values |
|---|---|---|---|---|
| 4A | 4-in | 2,789 | 400 | 0.019 |
| | 6-in | 2,344 | 382 | |
| 1A3M | 4-in | 2,925 | 521 | 0.024 |
| | 6-in | 2,611 | 527 | |
| 2A2M | 4-in | 2,994 | 465 | 0.361 |
| | 6-in | 2,779 | 522 | |
| 3A1M | 4-in | 2,890 | 477 | 0.167 |
| | 6-in | 2,459 | 213 | |
| All categories | 4-in | 2,887 | 477 | 0.002 |
| | 6-in | 2,554 | 469 | |

Following Eq. 1 and based on the obtained results, linear relationship between $f'_{c-4}$ and $f'_{c-6}$ can be established as follows, Eq. 5:

$$f'_{c-4} = 1.13 \times f'_{c-6} \quad (5)$$

Eq. 4 is based on all tested specimens. The correlation coefficient at 1.13 corresponds well with the values found from literature (Vandegrift and Schindler, 2006). Similar relations can be developed for each of the curing categories, based on the average $f'_c$ values presented in Table 5.

## Compressive strength- effect of curing method

It is observed in Figure 16 that the specimens from Category 2A2M demonstrate the highest $f'_c$ for both cylinder sizes, while Category 4A presents the lowest $f'_c$ for both cylinders. It was expected that longer moist curing will result in the development of more hydration products and thereby higher $f'_c$, however, the results present a different pattern. Cylinders from Category 1A3M, with the longest moist curing, demonstrate the lowest $f'_c$ among the moist cured cylinders; the second lowest $f'_c$ was achieved for one week of moist curing, while two weeks of moist curing resulted in the highest $f'_c$. Based on $f'_c$ results, it can be observed that moist curing improves $f'_c$, however only when moist curing is limited to two weeks. According to the results, two weeks of air and two weeks of moist curing represent the most beneficial curing type, resulting in the highest $f'_c$.

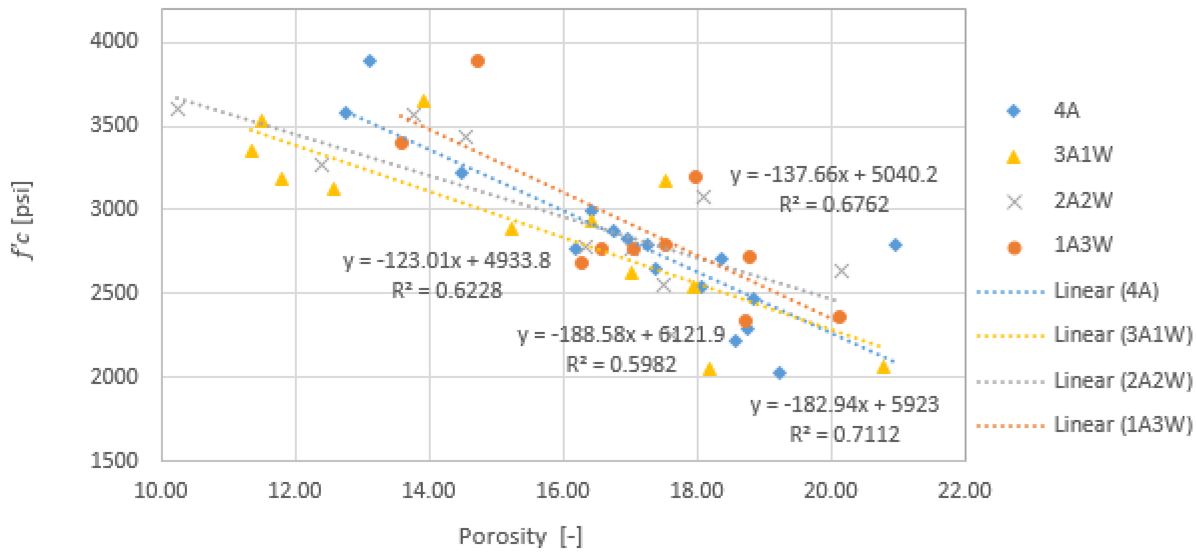
In order to assess statistically the impact of different curing categories on $f'_c$, t-tests were performed on the $f'_c$ from all curing categories, and p-values are listed in Table 6. As seen in

Table 6, differences in $f'_c$ caused by different curing methodologies are not statistically significant at 95 percent confidence level. Six-in cylinders show lower p-values comparing to 4-in cylinders, indicating the more significant impact of curing on $f'_c$. The comparison of curing methods 4A and 2A2M for 6-in cylinders resulted in a p-value of 0.061, which indicates a statistical significance at 90 percent confidence.

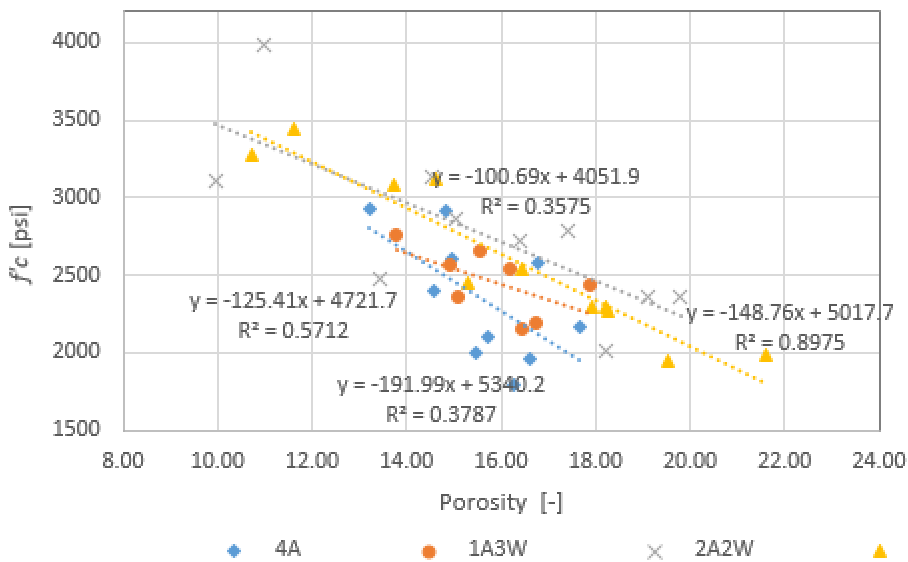
**Table 6- Results of Pearson t-test comparing $f'_c$ for different curing categories**

| **Curing category** | **p-values for 4-in cylinders** | | | | **p-values for 4-in cylinders** | | | |
|---|---|---|---|---|---|---|---|---|
| | 4A | 1A3M | 2A2A | 3A1M | 4A | 1A3M | 2A2A | 3A1M |
| 4A | Not applicable (NA) | 0.486 | 0.293 | 0.603 | NA | 0.206 | 0.061 | 0.449 |
| 1A3M | 0.486 | NA | 0.873 | 0.630 | 0.206 | NA | 0.403 | 0.118 |
| 2A2M | 0.293 | 0.873 | NA | 0.747 | 0.061 | 0.403 | NA | 0.484 |
| 3A1M | 0.603 | 0.630 | 0.747 | NA | 0.499 | 0.118 | 0.484 | NA |

Porosity is an essential property of PC, which affects its mechanical properties. To illustrate the effects of porosity on $f'_c$,

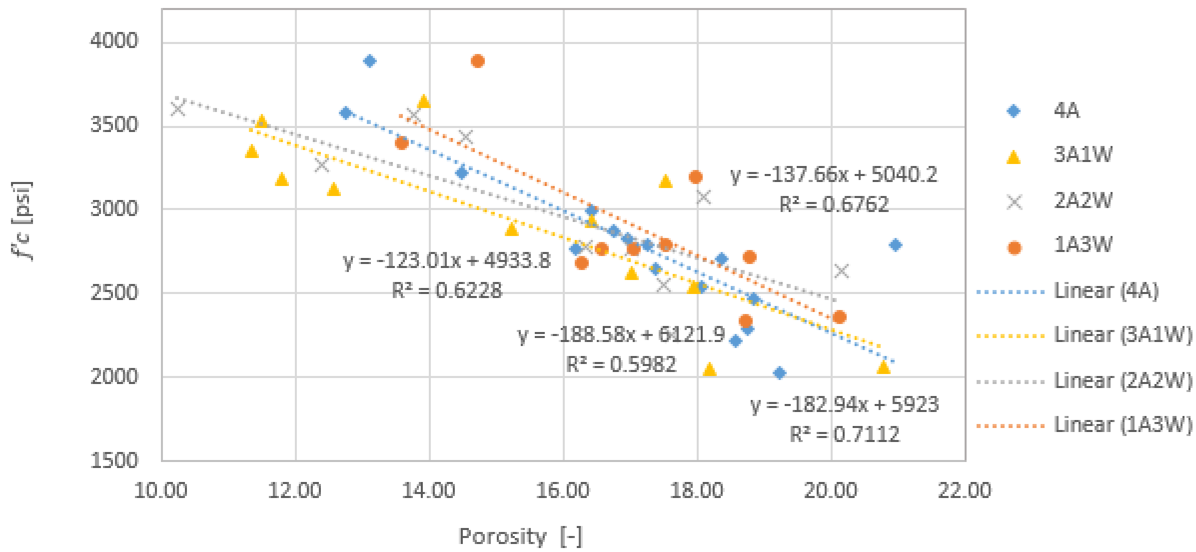



(a)

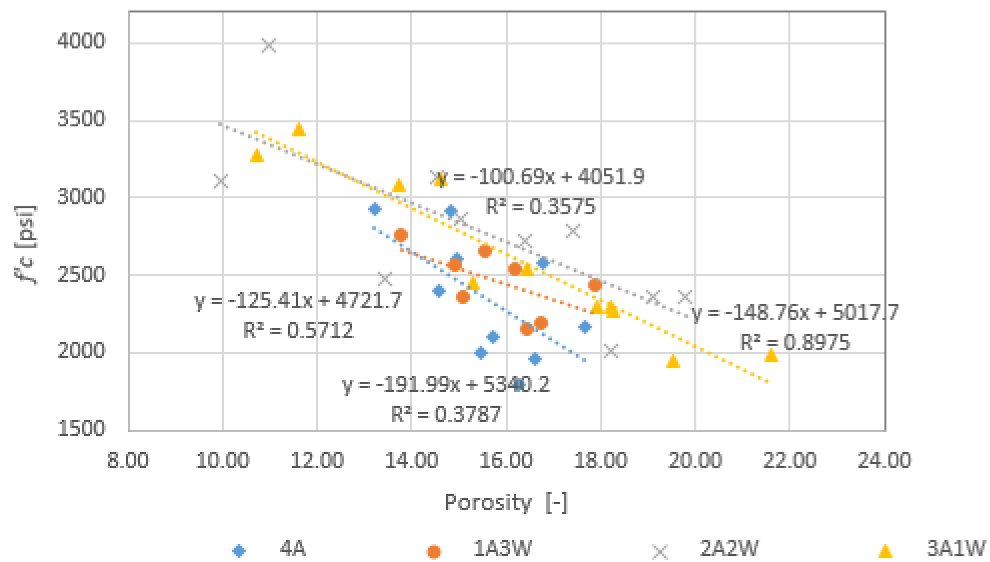



(b)

Figure 17 presents the results of $f'_c$ versus porosity for each tested specimen. As seen in




(a)

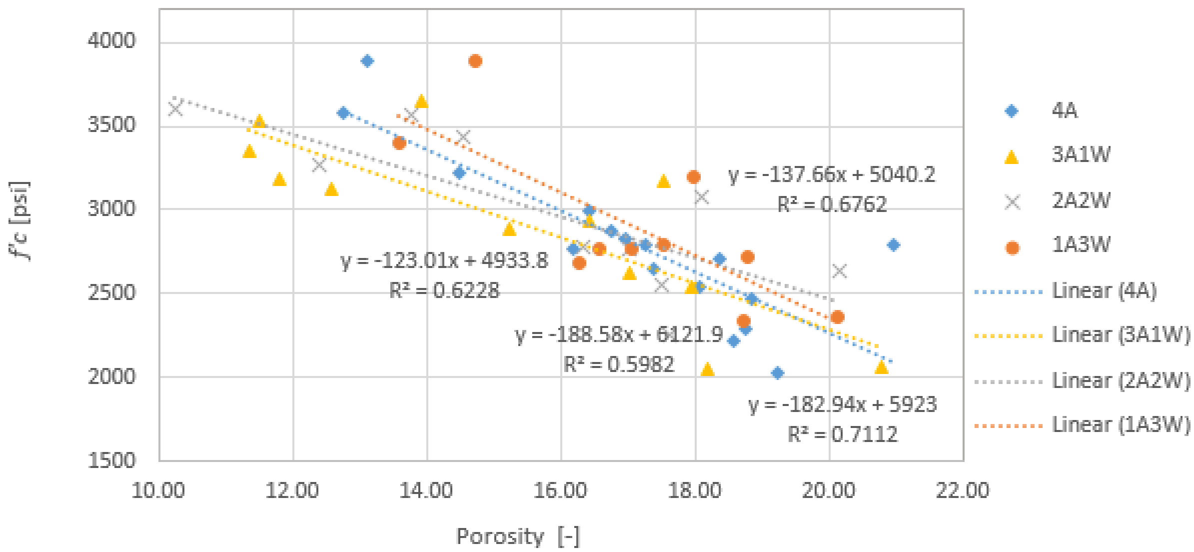



(b)

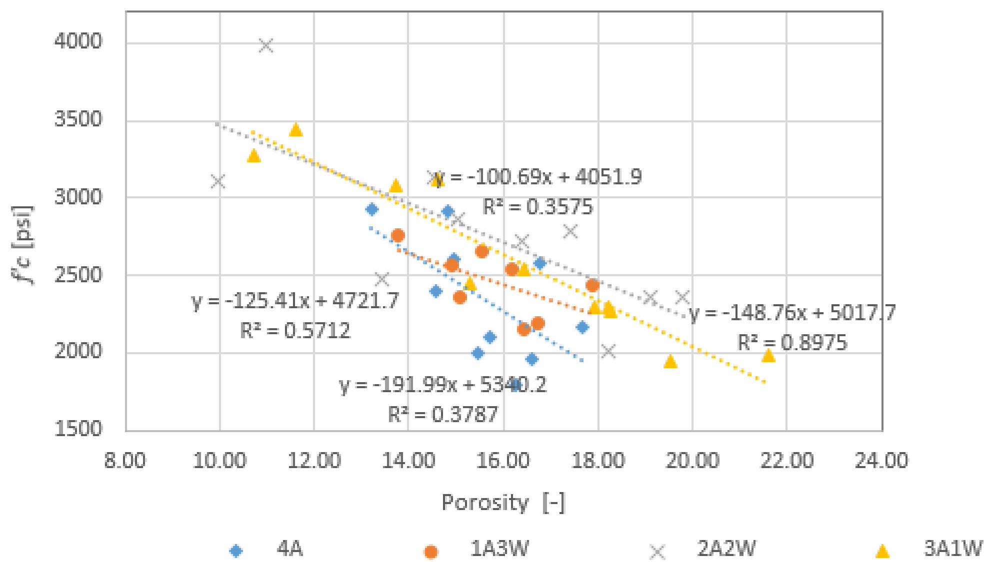
Figure 17, specimens with higher porosity generally present lower values of $f'_c$, as expected. The relationship between the porosity and $f'_c$ can be described as linear. A simple linear model can be established for all of the curing categories, in the form of Eq. 6:

$$f'_c = A * p + B \tag{6}$$

where $f'_c$ represents compressive strength in psi, p porosity in percent, and A and B regression coefficients. Table 7 features the regression coefficients for both specimen types and all curing categories, with the corresponding $R^2$ values, which describe the goodness of the fit for the linear relationships between porosity and $f'_c$. These models can be utilized for the estimation of 28-day $f'_c$, based on the implemented curing methodology.




(a)




(b)

**Figure 17- $f'_c$- $\phi$ relationship for (a) 4- and (b) 6-inch cylinders.**

**Table 7- Regression coefficients A and B from the Eq. 3, with the corresponding $R^2$.**

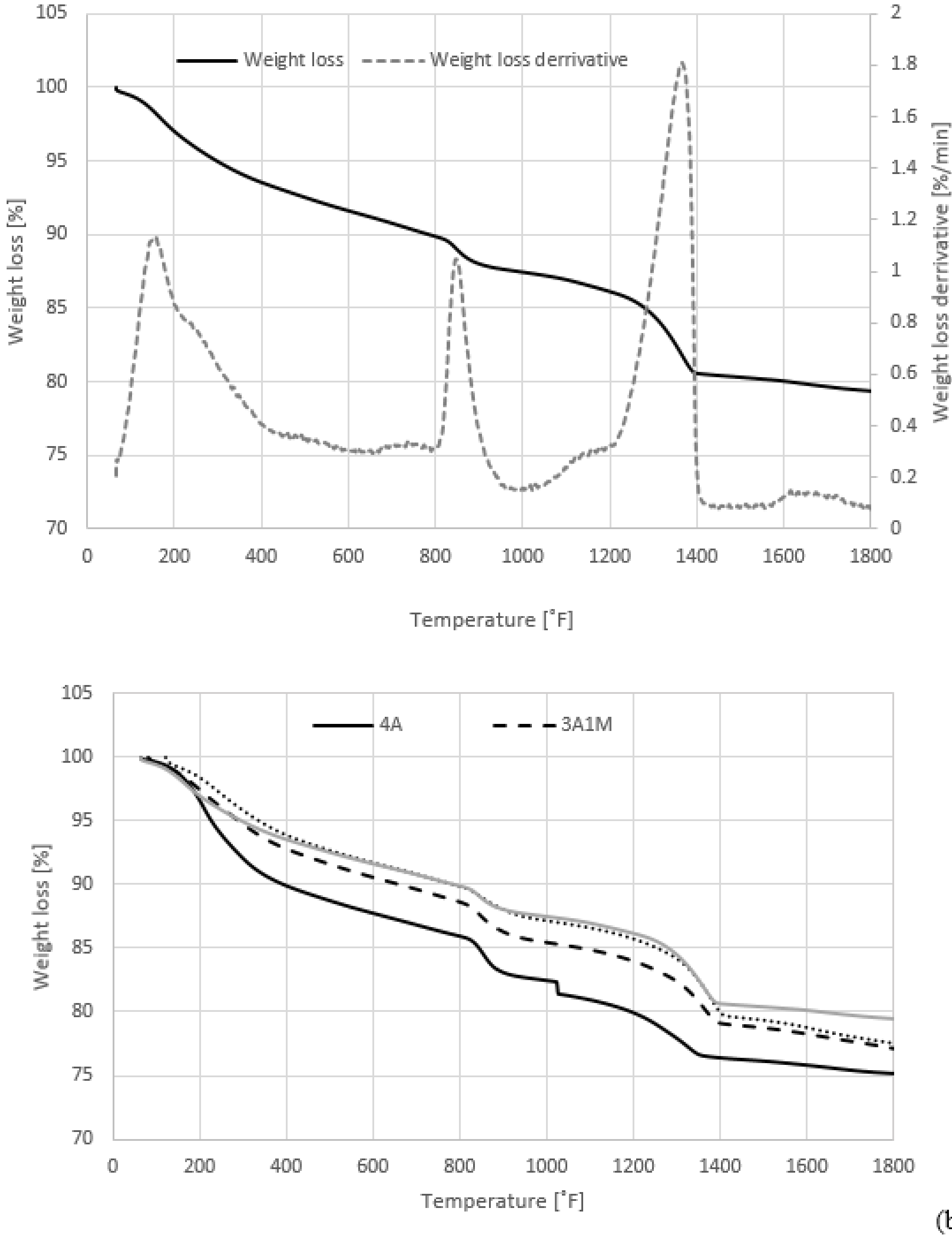
| Cylinder size | Curing category | Regression coefficient A | Regression coefficient B | $R^2$ value |
|---|---|---|---|---|
| **4-in** | 1 | -182.94 | 5923.0 | 0.711 |
| | 2 | -188.58 | 6121.9 | 0.598 |
| | 3 | -123.01 | 4933.8 | 0.623 |
| | 4 | -137.66 | 5040.2 | 0.676 |
| **6-in** | 1 | -191.99 | 5340.2 | 0.379 |
| | 2 | -100.69 | 4051.9 | 0.358 |
| | 3 | -125.41 | 4721.7 | 0.571 |
| | 4 | -148.76 | 5017.5 | 0.898 |

During the curing period, it was observed that the specimens subjected to moist curing in the fog room started to present white stains on the surface, as presented in Figure 19, which were assumed to be correlated to $Ca(OH)_2$ leaching. To further investigate the changes in the cement paste content and explain the reason for the decline in strength with prolonged moist curing, cement paste was sampled from one of the specimens from each curing category.

**Figure 18- Specimen from curing 1A3M at 28-day age, with white stains of leached materials.**

Approximately 3~5x$10^{-4}$ oz of paste was scraped from each specimen, pulverized, and used in the thermogravimetric analysis (TGA). The paste samples were heated from room temperature to 1800˚F, at the temperature rate 68˚F/min. The samples from curing categories 1A3M, 2A2M and 3A1M (categories that feature moist curing) were oven-dried at 212˚F for two hours, to eliminate free moisture. Figure 19 (a) displays the results of TGA test, represented by the weight loss and weight loss derivative, for the paste sample from curing category 1A3M as an example. The characteristic peaks in the weight loss derivative indicate the temperatures associated with significant mass losses. As seen in Figure 19 (a), three peaks occur at approximately: 180˚F, 850˚F, and 1370˚F. The first peak is typically correlated with the dehydration of C-S-H gel, while the second and third peaks are associated with the decomposition of $Ca(OH)_2$ and $CaCO_3$, respectively. Figure 19 (b) shows the results of TGA test, represented by the weight loss for the paste samples from four curing categories.

In order to quantify different phases of cement paste, loss on ignition (LOI) for the following temperature ranges was calculated, based on the literature (Bajza and Rouseková, 1983): 212~842˚F for the C-S-H, ettringite (Aft) and mono sulphate (Afm), 842~1112˚F for $Ca(OH)_2$, and 1112~1800 ˚F for $CaCO_3$. The results are presented in Table 8. As seen in Table 8, curing category 4A presents the highest content of C-S-H, Aft and Afm. For other three curing categories the amount of C-S-H, Aft and Afm decreases with the extension of the moist curing, which indicates that prolonged moist curing may lead to decalcification of C-S-H gel.




(a)

(b)

**Figure 19- TGA results: (a) weight loss and weight loss derivative for curing category 1A3M (b) weight loss for samples from four curing categories.**

Table 8 indicates that air curing (category 4A) is associated with the highest amount of $Ca(OH)_2$. Longer moisture curing yields in a drop in $Ca(OH)_2$ content. This trend is expected since $Ca(OH)_2$ represents a dissolvable cement paste compound that typically leaches due to the presence of water and/or chemical attack. $Ca(OH)_2$ leaching results in increased porosity and drop in strength with more severe effects than the effects of C-S-H decalcification on strength (Carde *et al.*, 1996; Carde and François, 1997). Finally, when the LOI associated with $CaCO_3$ is compared for different curing categories, it can be observed that curing category 2A2M shows the highest content of $CaCO_3$, at 9.05 percent. Moreover, curing category 4A demonstrates the lowest content of $CaCO_3$, followed by the categories 1A3M and 3A1M. The pattern in $CaCO_3$ content determined by TGA for different curing categories corresponds well to the trends observed previously for $f'_c$. Curing categories with higher content of $CaCO_3$ present higher $f'_c$.

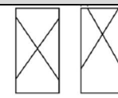
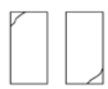
**Table 8- LOI based on different temperature ranges for four curing categories based on TGA**

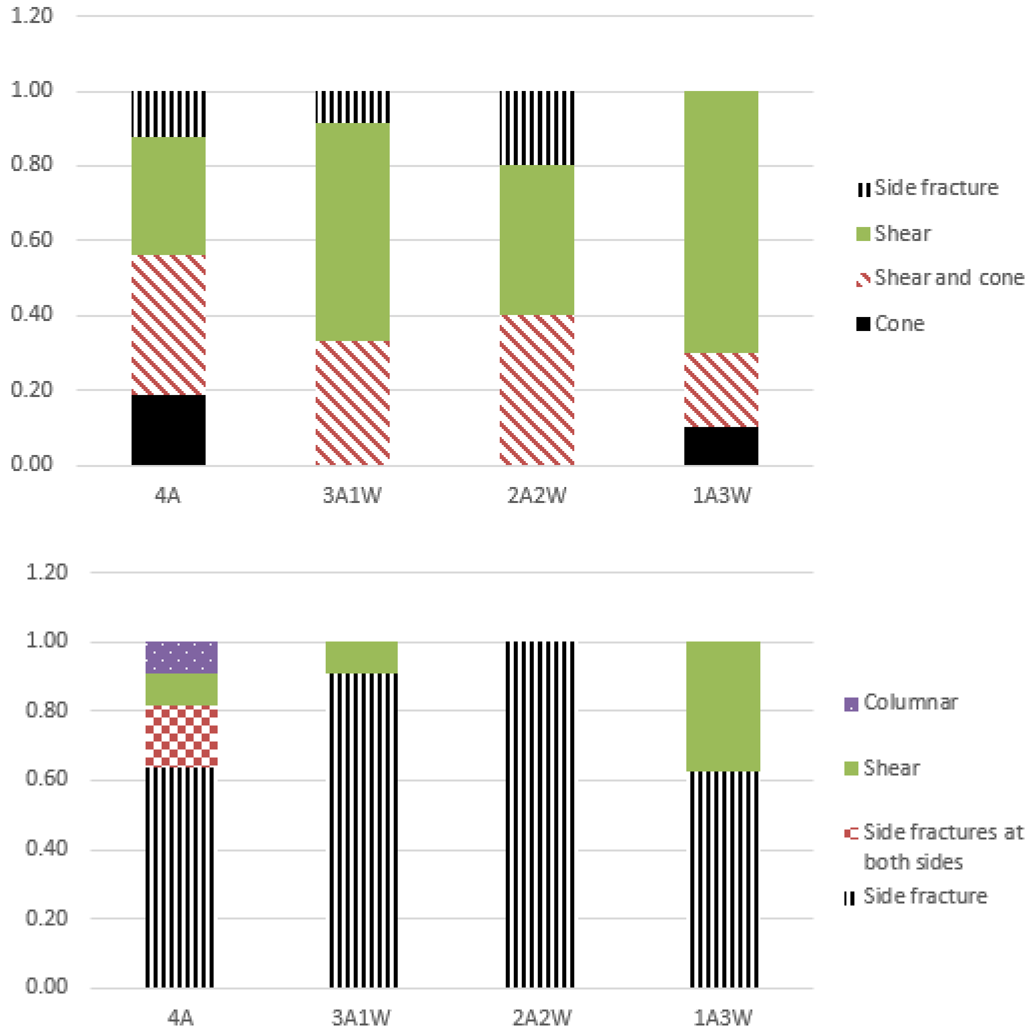
| **Temperature range** | **Cement paste compound** | **LOI (%) based on curing category** | | | |
|---|---|---|---|---|---|
| | | **4A** | **3A1M** | **2A2M** | **1A3M** |
| 212~842˚F | C-S-H, Aft, Afm | 10.75 | 9.36 | 8.99 | 7.52 |
| 842~1112˚F | $Ca(OH)_2$ | 4.29 | 2.96 | 2.71 | 2.34 |
| 1112~1800 ˚F | $CaCO_3$ | 5.72 | 7.71 | 9.05 | 7.47 |

## Failure types

Failure types, as specified in ASTM C39, were recorded for each tested specimen during the $f'_c$ test. Moreover, three additional failure types: columnar cracks, shear with the cone, and side fracture on both ends, were identified and added to the ones defined by the standard. All of the failure types observed in this study are presented in Table 9 by their ASTM C39 designation (if available), scheme, description, and photograph.

**Table 9- Observed failure types after $f'_c$ test.**

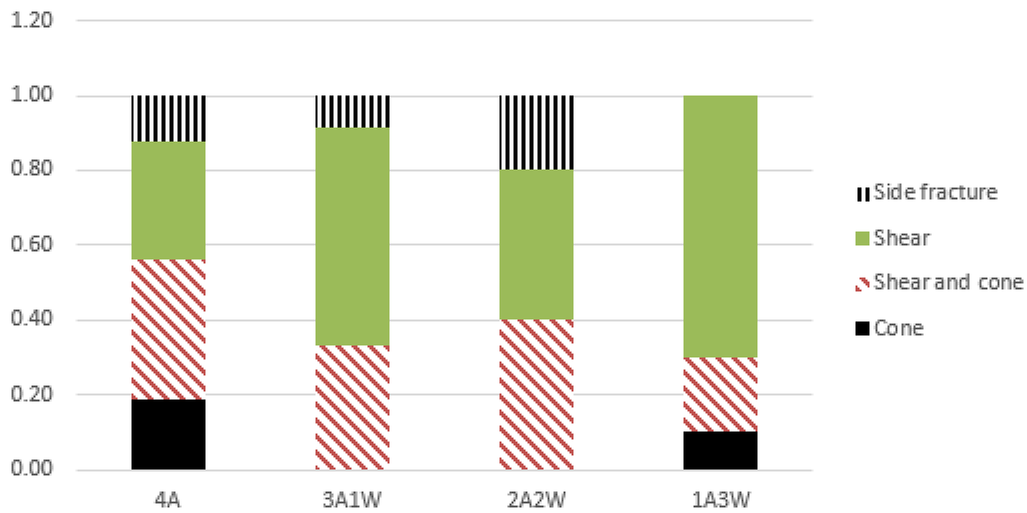
| **Failure type name** | Columnar cracks | Cone and shear | Cone |
|---|---|---|---|
| **Failure type from ASTM C39** | Not available (NA) | NA | Type 1  |
| **Description** | Columnar cracks propagate vertically and evenly around the specimen. | Well-formed cone at one end, prominent diagonal (shear) cracks on another. | Well-formed cones on both ends, top and bottom intact. |
| **Photograph** |  |  |  |
| **Failure type name** | Shear | Side fractures | Side fractures on both ends |
| **Failure type from ASTM C39** | Type 4  | Type 5  | (NA) |
| **Description** | Diagonal fracture throughout the specimen, without cracking of top/bottom. | Side fractures at top/bottom; resembles shear failure, with cracked top or bottom. | Side fractures at both top and the bottom simultaneously. |
| **Photograph** |  |  |  |



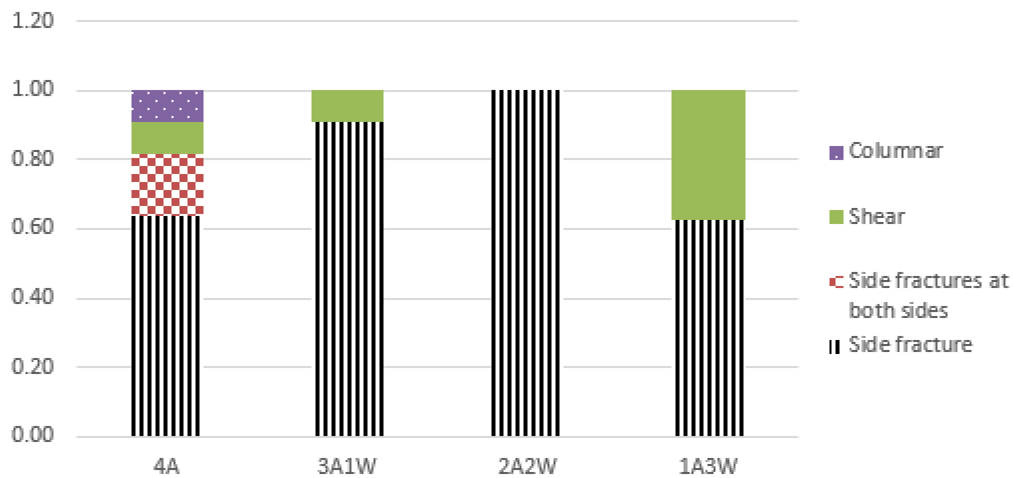
(a)

(b)

Figure 20 presents the percentage occurrence of different failure types for 4-in (a) and 6-in cylinders (b), based on the curing category. As seen in




(a)




(b)

Figure 20 (a), shear failure was the dominant failure type for 4-in cylinders across all curing methods. Approximately 48 percent of the tested 4-in cylinders in total failed in shear. The next most prevalent failure type was cone and shear, followed by the side fracturing, with approximately 33 and 10 percent, respectively, for all tested 4-in cylinders. Finally, 8.3 percent of all 4-in cylinders expressed cone type of failure. In the case of 6-in cylinders (

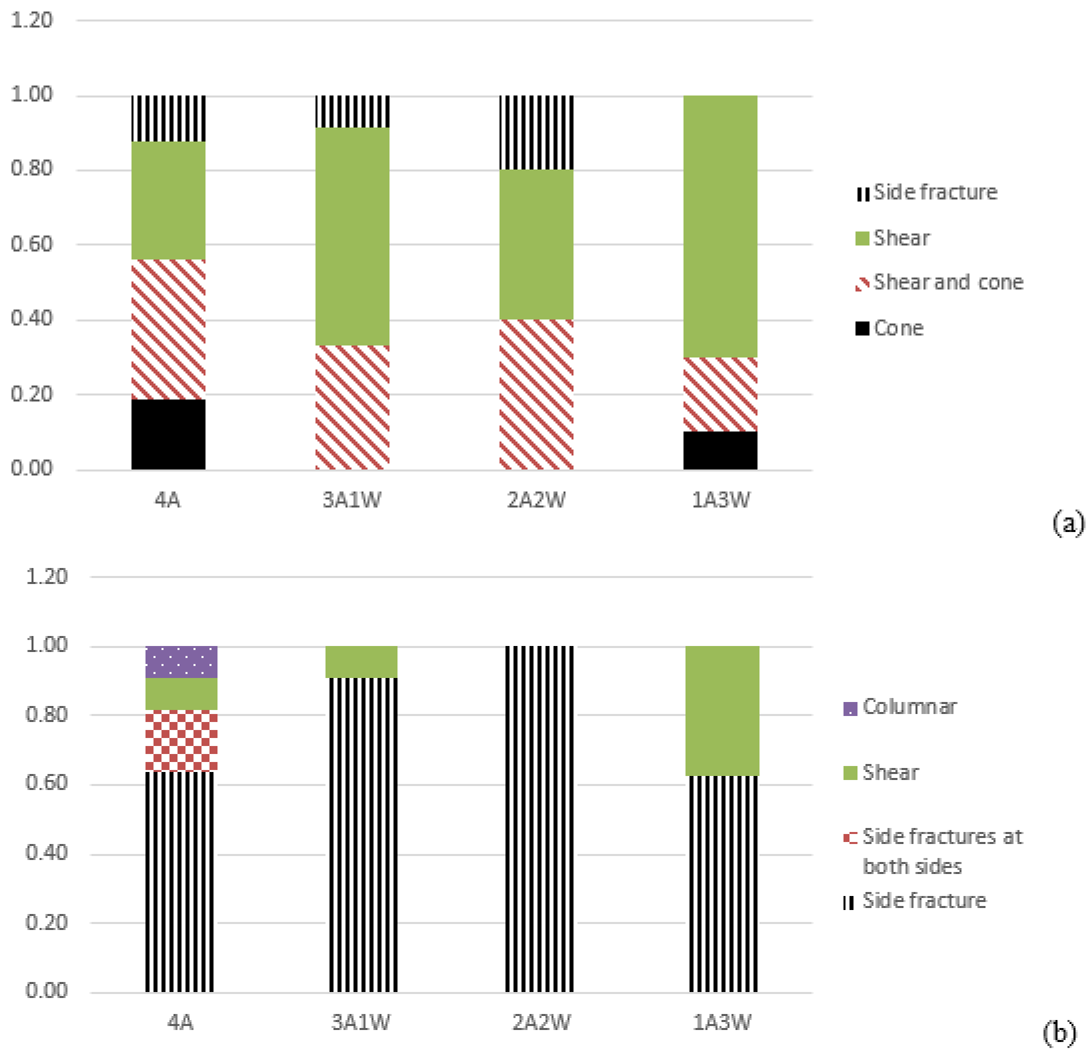



Figure 20, b), approximately 80 percent of tested specimens failed in a side fracture, which was the dominant failure type. Second most common failure type was shear, with 12.5 percent occurrence. Side fracture on both ends was recorded for 5 percent of the tested 6-in cylinders. Finally, one 6-in cylinder exhibited failure in columnar cracks.

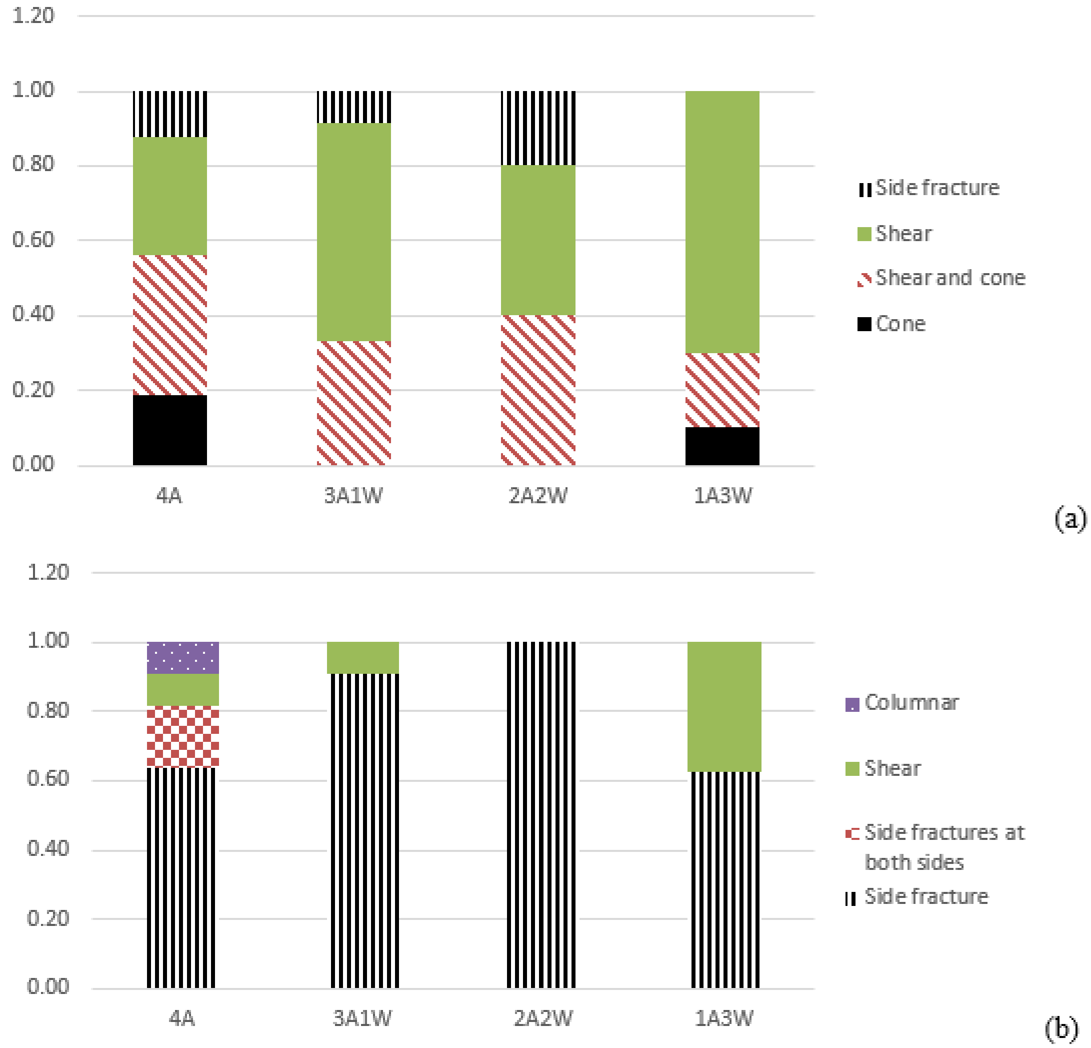
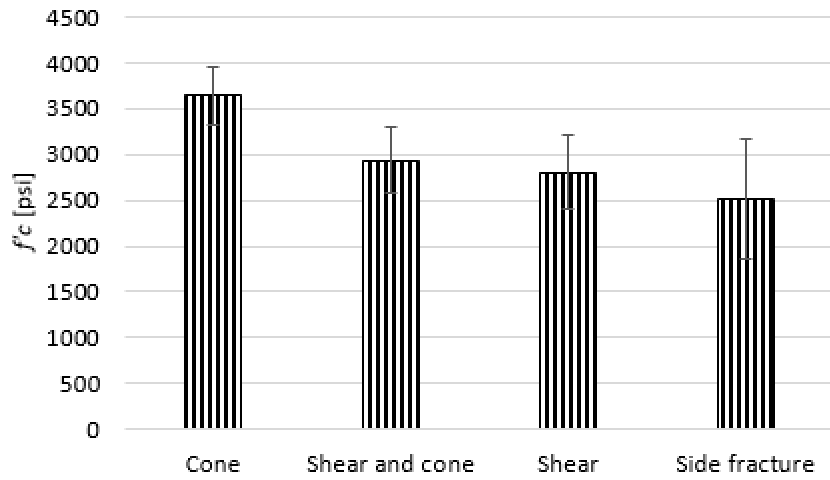
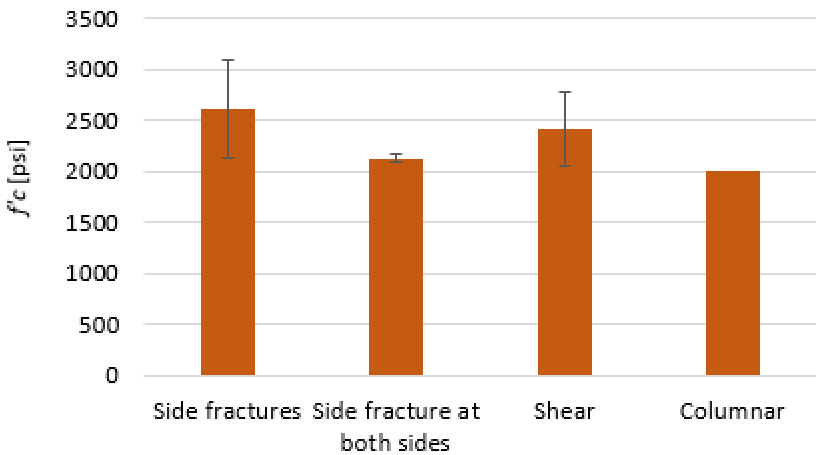



**Figure 20- Occurrence of different failure types on $f'_c$ test (a) 4- and (b) 6-in cylinders.**




(a)




(b)

Figure 21 shows the strength of tested specimens from all curing categories, based on the observed failure type. Based on

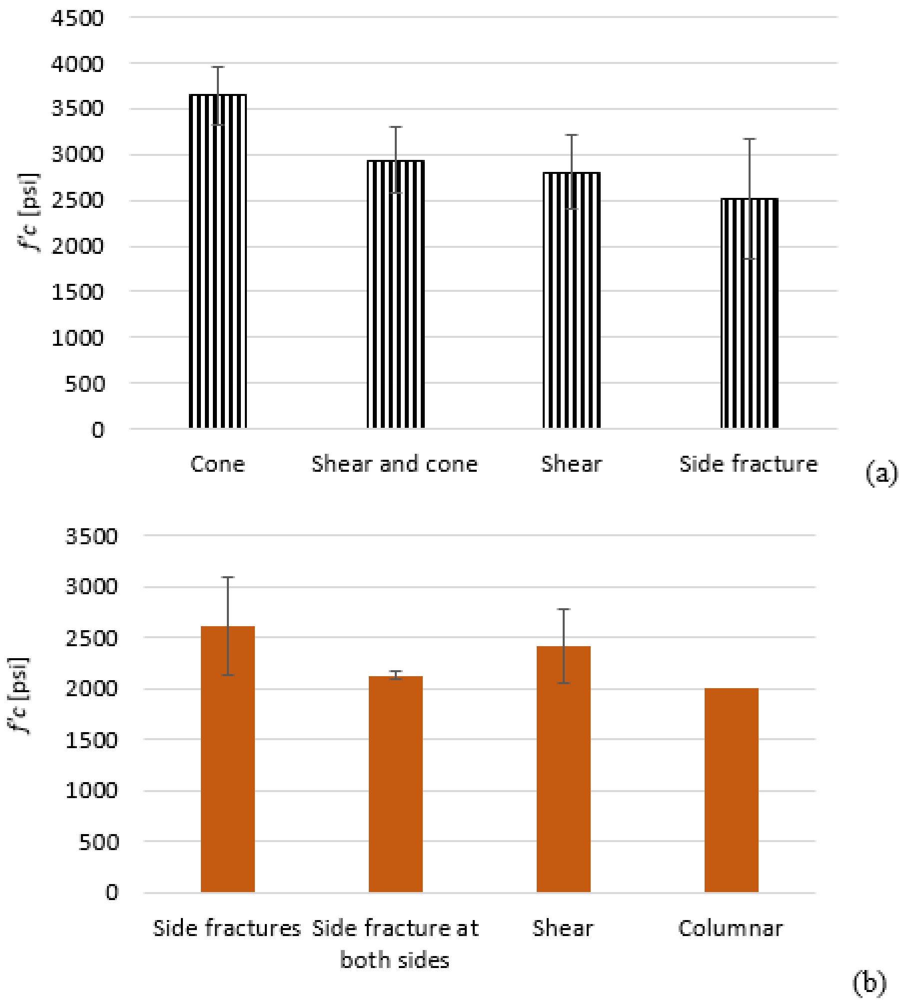
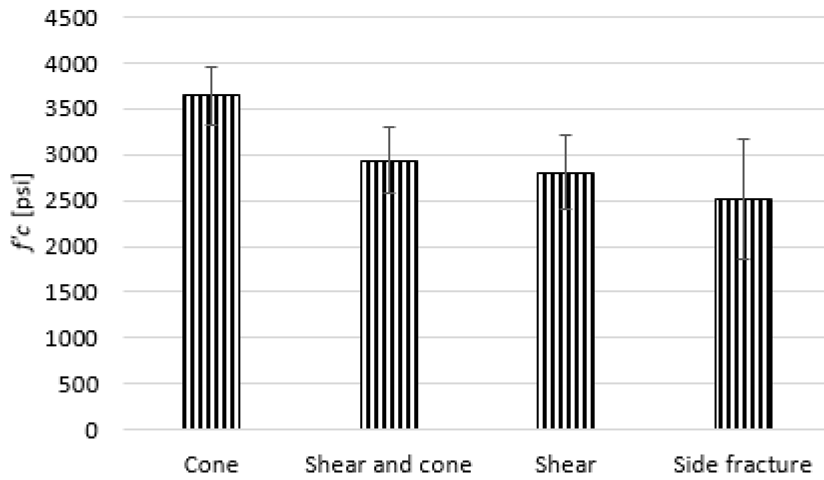
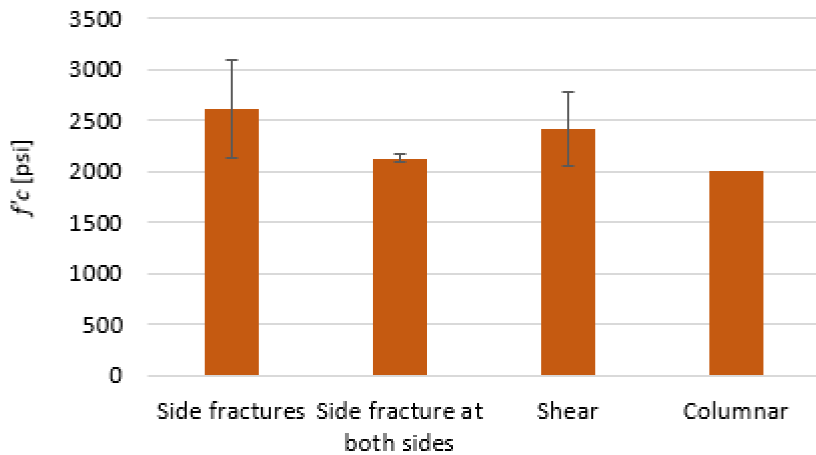



Figure 21-a, 4-in cylinders that showed cone failure have the highest $f'_c$, at 3,643 psi on average. Next are the 4-in cylinders in shear and cone failure demonstrated an average $f'_c$ of 2,934 psi. The specimens failed in shear, the most frequent failure type, exhibited average $f'_c$ of 2,802 psi. The side fracture failures showed the lowest values of $f'_c$ at 2,518 psi. For 6-in cylinders, the dominant failure type, side fracture, was coupled with the highest value of $f'_c$, at




(a)




2616 psi, as seen in

(b)

Figure 21 (b). Specimens failed in shear presented the average $f'_c$ at 2418 psi. Failures in double side fracture and columnar cracking were present in this study with two and one specimens, respectively. Hence, it is not possible to draw strong conclusions regarding the $f'_c$ associated to these two failure types for 6-in cylinders.

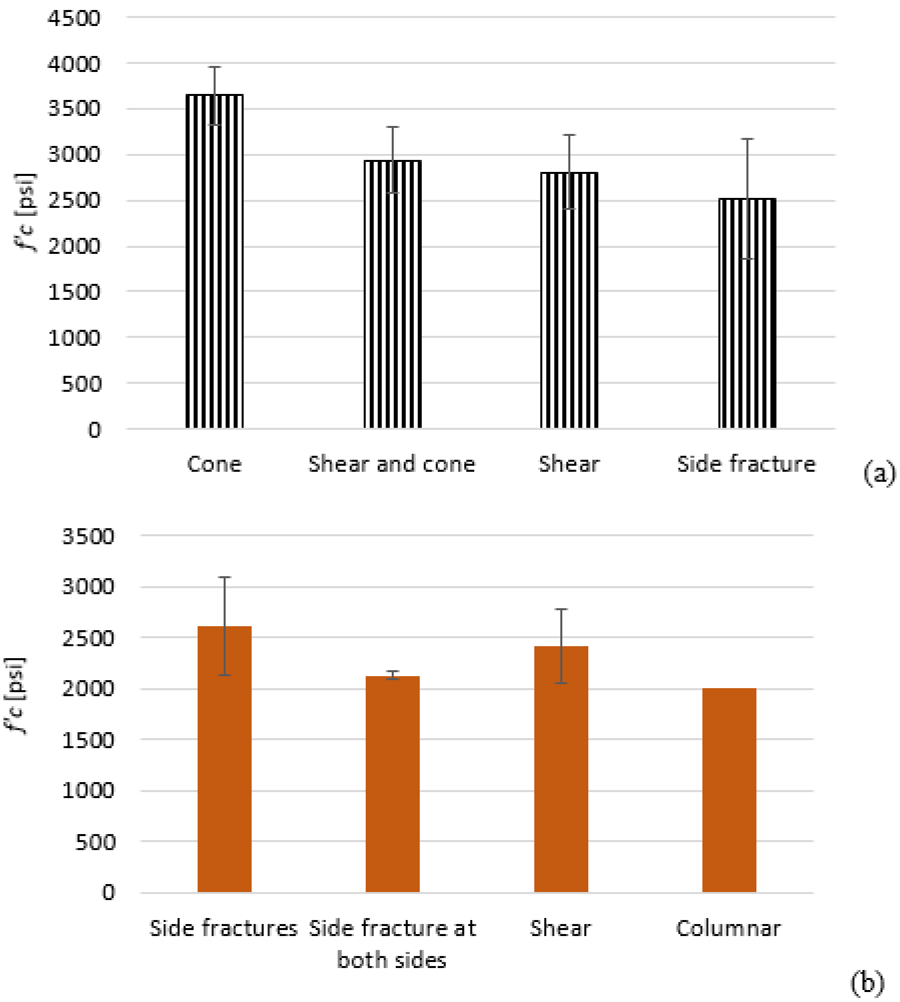
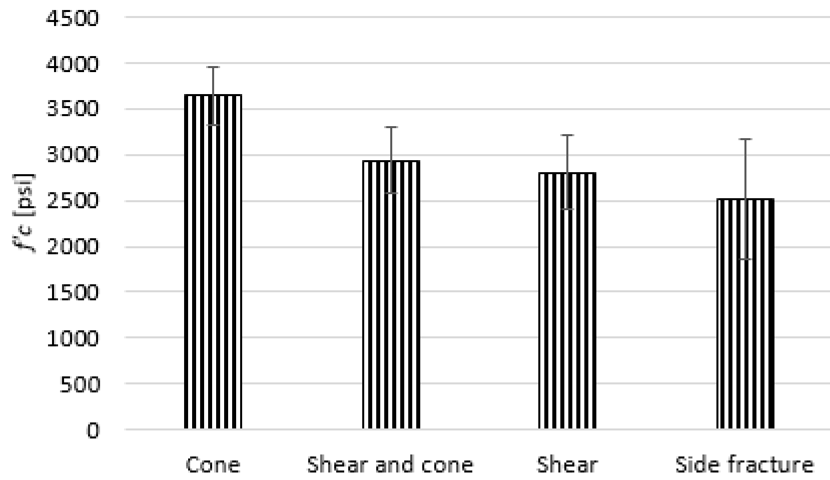
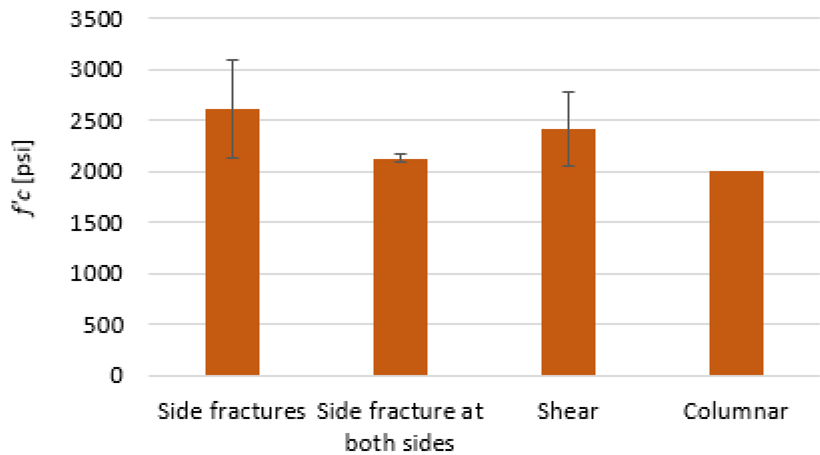



**Figure 21- Compressive strength (*f'*$_c$) of PC versus the recorded failure type (all curing categories included) for (a) 4- and (b) 6-in cylinders.**

Failure types and corresponding *f'*$_c$ were tested as a part of an earlier study by the authors on PC reinforced with Cured Carbon Fiber Composite Material (CCFCM) (Rangelov *et al.*, 2016). Tests were performed on four 28-day old 4-in cylinders on each of the seven tested mixture design (one control PC mixture and six reinforced PC mixtures with different dosages and sizes of CCFCM particles). Figure 22 presents the summarized results from the earlier study in terms of *f'*$_c$ as a function of failure types on a total of 28 4-in cylinders. When the results from Figure 22 are compared with the results presented in



(a)



(b)

Figure 21-a, it can be concluded that the values of $f'_c$ based on failure types from both studies agree closely (the differences range from 5 for shear failure, to 16 percent for side fracture). Authors will continue to build the PC failure type database to form a comprehensive failure database for various level of PC strength.

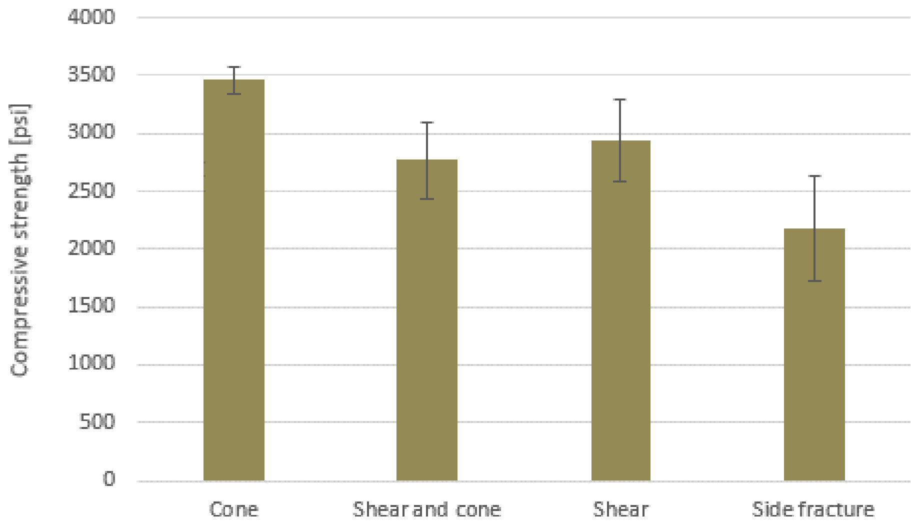



**Figure 22- Compressive strength vs. failure type for 4-in cylinders tested as a part of the earlier study (Rangelov *et al.*, 2016). The total of 28 tested specimens included.**

## Load-displacement behavior

The load-displacement curve was recorded for twelve 6-in cylinders from the curing categories: 4A, 2A2W, and 3A1W.

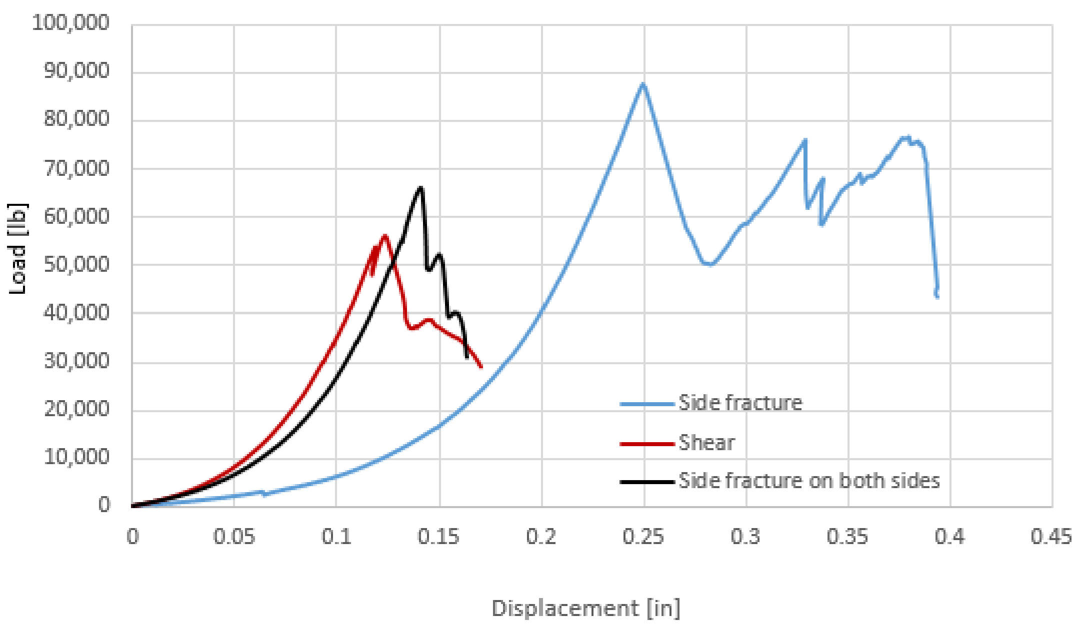



Figure 23 presents an example load-displacement curve for different three failure types: side fracture, shear failure and side fracture on both sides. The remaining recorded load-displacement curves are provided in Appendix A.

Specimens that showed shear failure and side fracture on both sides exhibit substantially lower peak-load and residual strength comparing to the specimen with side fracture failure. The shear failure type is associated with a brittle behavior, in which a sudden drop in load is evident. After the peak load no residual load can be applied to the specimen. A similar behavior can be seen with the specimen with side fractures on both sides.

However, the specimen with side fracture failure demonstrates a considerably higher peak load and residual strength to carry further loading post the peak load, with several cycles of hardening. It is noteworthy that side fracture was the most common failure type observed in this study, therefore more specimens with alternate failure types are needed to confirm the trends observed in the load-displacement curves.

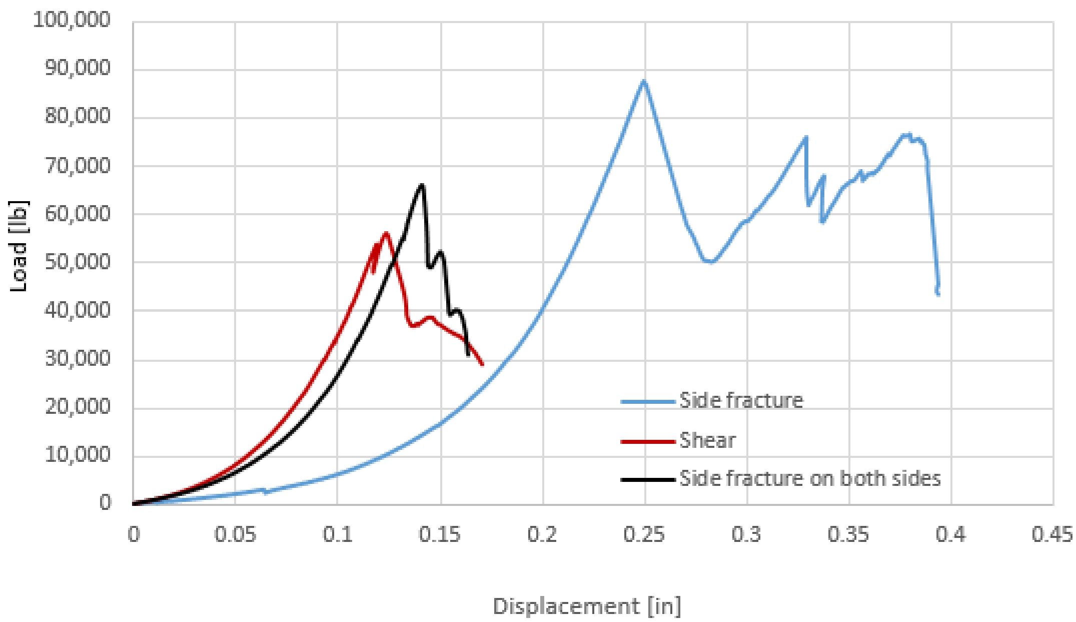



**Figure 23- Load-displacement chart for the 6-in specimens and three observed failure types: side fracture on one side, side fracture on both sides shear failure.**

## CONCLUSIONS

An experimental study was conducted to evaluate different test methods for quality evaluation of pervious concrete in the field and in the laboratory. Special focus was placed on the evaluation of the suitability of simple tests such as fresh density, hardened porosity and infiltration rate, as well as compressive strength testing. The required specimens were cast during PC placement on the Vashon Island Ferry Terminal on two paving days in summer 2016. In evaluating the tests mentioned above, the suitability of the method of casting specimens in the field and the effects of cylinder size and curing conditions on 28-day compressive strength of PC was investigated. Four curing categories of four weeks of air curing (4A), three weeks of air and one week of moist curing (3A1M), two weeks of air and two weeks of moist curing (2A2M), and one week of air and two weeks of moist curing (1A3M) were evaluated in the study. The main findings from the study are:

The two cylinder sizes cast from the tested mixture demonstrated close values in porosity (around 16 percent on average) and hardened density (around 131.5 lb/ft$^3$ on average.) This finding for the cylinders tested in this study implies that either cylinder size may be cast for evaluation of hardened density and porosity. More testing in future projects can further confirm this finding.

The hardened density of both cylinder sizes agreed with the fresh density determined in the field during placement (maximum difference of two percent.) This observation confirms that the implemented casting and compaction method was suitable in casting specimens that represented the target density in the field. The method described in this report is recommended to cast and compact specimens for strength testing.

The average infiltration rates were 804 and 689 in/h for 4- and 6-in cylinders respectively, which is within the accepted range for PC. The 6-in cylinders demonstrated lower and more uniform infiltration rates on average comparing to the 4-in cylinders because they were cast and compacted in three lifts versus two lifts for 4-in cylinders.

Four-in cylinders showed higher values of 28-day $f'_c$, compared to 6-in cylinders by 7.7-19 percent. Based on the tested specimens in this study, the 28-day $f'_c$ of 6-in cylinders can be obtained by multiplying the test results of 4-in cylinders by a correlation factor of 1.13. More testing is required to further populate the developed database and suggest a reliable correlation coefficient between the strength of the two cylinder sizes.

Curing category 2A2M resulted in the highest value of 28-day $f'_c$, while the specimens from curing category 4A had the lowest strengths. Overall, air curing resulted in a relatively low standard deviation in $f'_c$, and minimal C-S-H and $Ca(OH)_2$ loss according to TGA testing.

However, two weeks of air and two weeks of moist curing yielded the highest $f'_c$, and a comparatively low standard deviation. Further, TGA testing showed that longer moist curing leads to more loss of C-S-H and $Ca(OH)_2$. Therefore, two weeks of air and two weeks of moist curing appear to provide the highest and most reliable test results for strength testing of PC, based on the specimens tested in this study. More testing is required to confirm this recommendation as the proper curing method for PC strength testing.

During compressive strength testing, the 4- and 6-in cylinders most commonly failed in shear and side fracture, respectively. The two cylinder sizes generally showed different modes of failure, which was most likely caused by the difference in the compaction method of two lifts for 4- versus three lifts for 6-in cylinders.

This preliminary study showed that fresh density, hardened density/porosity and hardened infiltration rate are simple tests that can provide insightful information regarding quality of the PC mixture. Compressive strength testing on properly cast and cured specimens, tested at a modified loading rate can provide reliable evaluation information. In order to confirm the recommendations in this study for sampling, curing and testing of PC future research should include testing of a variety of PC mixtures using a sufficient number of specimens. Based on the results of this study, future assessment of weight loss in PC paste caused by the prolonged exposure to water is recommended, especially considering the extended exposure of PC pavements to stormwater runoff.

## FUTURE RESEARCH

This study was a preliminary step towards identifying suitable tests for quality acceptance of pervious concrete. The study's duration was limited to one summer and one paving project and two paving dates. Therefore, the study was limited to testing one pervious concrete mixture and therefore a restricted number of tested specimens. Future research needs to include additional mixture designs to add to the database of test results in this study to develop robust inter-relations between the tested properties and finally develop standardized testing protocols. Other strength properties such as flexural strength and modulus of elasticity that are required in the pavement design should also be established for a variety of mixture designs.

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## REFERENCES

ACI. 522R-10. 2010. Report on Pervious Concrete. ACI Committee, 522.

ACI. 522R-13. 2013. Report on Pervious Concrete. ACI Committee.522.

Aitcin, P. C., Miao, B., Cook, W. D., & Mitchell, D. (1994). Effects of size and curing on cylinder compressive strength of normal and high-strength concrete. Materials Journal, 91(4), 349-355.

ASTM. C39/C39M-05, 2005, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2005, DOI: 10.1520/ C0039_C0039M-05E01.

ASTM C192/C192M-15. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken, PA, 2015, DOI: 2 10.1520/ C0192_C0192M-15.

ASTM C944/C944M-12, Abrasion Resistance of Concrete or Mortar Rotating-Cutter Method, ASTM International, West Conshohocken, PA, 2012, DOI: 2 10.1520/C0944_C0944M-12.

ASTM C1701/C1701M-09, Standard Test Method for Infiltration Rate of In Place 1 Pervious Concrete, ASTM International, West Conshohocken, PA, 2009, DOI: 2 10.1520/C1701_C1701M-09.

ASTM C1754/C1754M-12, Standard Test Method for Density and Air Void Content of Pervious Concrete, ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/C1754_C1754M-12.

ASTM. C31/C31-M, 2012, Standard Practice for Making and Curing Concrete Test Specimens in the Field, ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/C0031-12.

ASTM. C1688/C1688-M, 2014, Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete, ASTM International, West Conshohocken, PA, 2014, DOI: 10.1520/C1688-14.

Bajza, A., & Rouseková, I. (1983). Effect of heat treatment conditions on the pore structure of cement mortars. Cement and Concrete Research, 13(5), 747-750.

Carde, C., & François, R. (1997). Effect of the leaching of calcium hydroxide from cement paste on mechanical and physical properties. Cement and Concrete Research, 27(4), 539-550.

Carde, C., François, R., & Torrenti, J. M. (1996). Leaching of both calcium hydroxide and CSH from cement paste: Modeling the mechanical behavior. Cement and concrete research, 26(8), 1257-1268.

CRMCA–Colorado Ready Mixed Concrete Association. (2009). Specifier's Guide for Pervious Concrete Pavement Design–Version 1.2. 24p.

Dong, Q., Wu, H., Huang, B., Shu, X., & Wang, K. (2012). Investigation into laboratory abrasion test methods for pervious concrete. Journal of Materials in Civil Engineering, 25(7), 886-892.

Eisenberg, B., Lindow, K. C., & Smith, D. R. (Eds.). (2015). Permeable Pavements. American Society of Civil Engineers.

Haselbach, L., Boyer, M., Kevern, J., & Schaefer, V. (2011). Cyclic heat island impacts on traditional versus pervious concrete pavement systems. Transportation Research Record: Journal of the Transportation Research Board, (2240), 107-115.

ISO 177851-1:2016. Testing Methods for Pervious Concrete--Part 1: Infiltration Rate. ISO: Geneva, Switzerland.

Kevern, J. T., Haselbach, L., & Schaefer, V. R. (2012). Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems. Journal of Heat Island Institute International Vol, 7(2).

Kevern, J. T., Schaefer, V. R., Wang, K., & Suleiman, M. T. (2008). Pervious concrete mixture proportions for improved freeze-thaw durability. Journal of ASTM International, 5(2), 1-12.

NRMCA. Pervious in Practice: Methods, Materials and Mixtures, National Ready Mixed Concrete Association (NRMCA), Silver Spring, MD, www.nrmca.org, 2016.

Grace Concrete Products, G. C. V- MAR VSC500, Rheology Modifying Admixture for Pervious Concrete, 2010. Available from https://grace.com/construction/en-us/concrete-technology/V-MAR-VSC500.

Grace Concrete Products, Recover, Hydration  Stabilizer, 2013.

Available from https://gcpat.com/construction/en-us/Documents/Recover-5J_Recover.pdf.

Rangelov, M., Nassiri, S., Haselbach, L., & Englund, K. (2016). Using carbon fiber composites for reinforcing pervious concrete. Construction and Building Materials, 126, 875-885.

Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). Pervious concrete pavements (No. PCA Serial No. 2828). Skokie, IL: Portland Cement Association.

Vandegrift, D., & Schindler, A. (2006). The effect of test cylinder size on the compressive strength of sulfur capped concrete specimens. Highway Research Center and Department of Civil Engineering at Auburn University, 83.

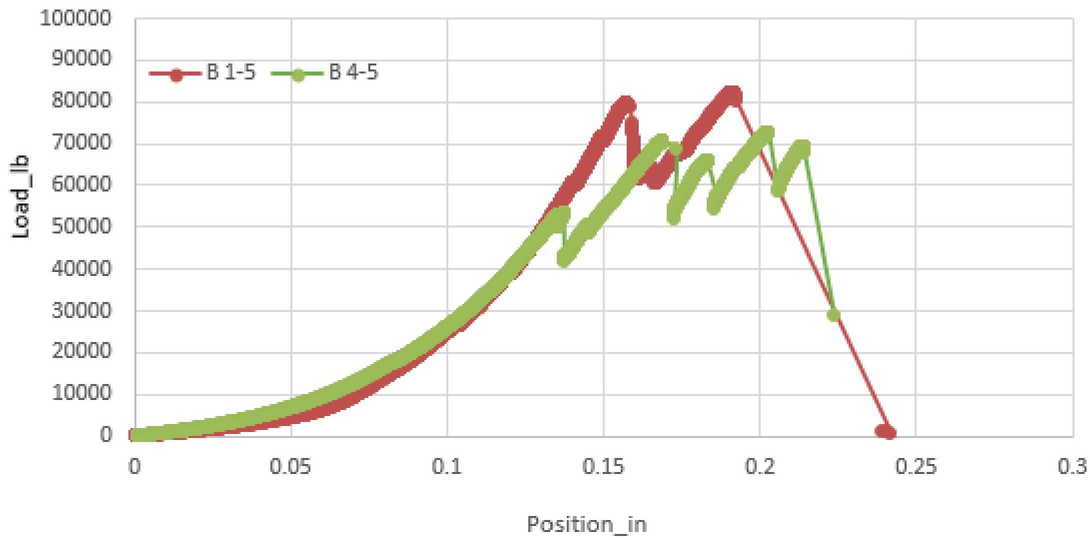
Washington Aggregate and Concrete Association: Pervious Concrete. Retrieved from: http://www.washingtonconcrete.org/pervious-concrete, October 2016.

WSDOT: Vashon Ferry Terminal Construction Lanes Layout. Available from http://www.wsdot.wa.gov/NR/rdonlyres/E29345CD-175B-4F41-939F-22153AED457E/0/VashonPhase3_FINAL_041916.pdf

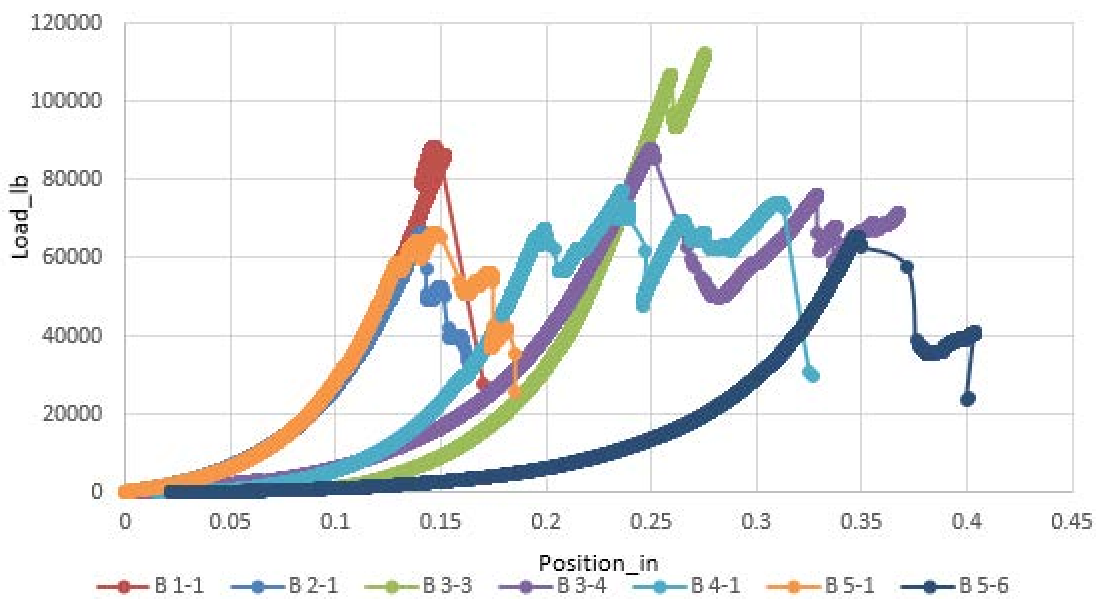
## APPENDIX

This chapter contains the load-displacement curves of the 6-in cylinders from three curing categories.

Curing category 4A




Curing category 2A2W



Curing category 3A1W