THE USE OF SYNTHETIC BLENDED FIBERS TO REDUCE CRACKING RISK IN HIGH PERFORMANCE CONCRETE

FINAL PROJECT REPORT

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Technical Report Documentation Page

1. Report No.
2012-S-OSU-0011

2. Government Accession No.
01538104

3. Recipient's Catalog No.

4. Title and Subtitle
The Use of Synthetic Blended Fibers to Reduce Cracking Risk In High Performance Concrete

5. Report Date
September 15, 2014

6. Performing Organization Code

7. Author(s)
Jason H. Ideker, José Bañuelos

8. Performing Organization Report No.
11-739437

9. Performing Organization Name and Address

PacTrans
Pacific Northwest Transportation Consortium, University Transportation Center for Region 10
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Seattle, WA 98195-2700

Oregon State University
101 Kearney Hall
Corvallis, OR 97330

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTRT12-UTC10

12. Sponsoring Organization Name and Address
United States of America
Department of Transportation
Research and Innovative Technology Administration

13. Type of Report and Period Covered
Research 9/1/2012-7/31/2014

14. Sponsoring Agency Code

15. Supplementary Notes
Report uploaded at www.pacTrans.org

16. Abstract

Transportation departments have observed varying degrees of cracking in their concrete structures. Cracking of high performance reinforced concrete structures, in particular bridge decks, is of paramount concern to Pacific Northwest Departments of Transportation. Cracking at early ages (especially within the first year after placement) results in additional costs and a significant maintenance burden to ODOT. The causes behind cracking in high performance concrete are well known and documented in the existing literature. Recent research at Oregon State University under two separate projects: SPR 711 and SPR 728 has elucidated the propensity for shrinkage in high performance concrete mixtures mainly used for concrete bridge decks. These previous projects identified 1) mitigation methods to reduce shrinkage (e.g. internal curing using fine lightweight aggregates –FLWA, and/or the use of shrinkage reducing admixtures SRA) and 2) proposed shrinkage measurement techniques and thresholds/limits using those techniques that should reduce shrinkage and early-age cracking risk. The aim of this project was to investigate a relatively new technique to control early-age cracking; the use of blended size polypropylene fibers in high performance concrete mixtures. The key findings from this work were that the use of drying shrinkage test methods alone, without the capture of cracking risk, showed that the inclusion of fibers did not reduce drying shrinkage in unrestrained specimens. However, in restrained testing (where the possibility of crack formation is promoted) the fibers were able to 1) reduce the rate of stress generation in specimens 2) prolong the time to cracking in the restrained ring test (ASTM C 1581) and 3) reduce the crack widths and the growth of cracks once cracking did initiate. As a result the use of blended fibers in high performance concrete points to another viable solution for reducing the risk of cracking in service.

17. Key Words
High Performance Concrete, Drying Shrinkage, Cracking

18. Distribution Statement
No restrictions.

19. Security Classification (of this report)
Unclassified.

20. Security Classification (of this page)
Unclassified.

21. No. of Pages

22. Price
NA

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Acknowledgments

Special thanks go to the Infrastructure Materials Group Graduate and Undergraduate students. We would like to thank Mr. Tyler Deboodt and Dr. Tengfei Fu for their advisement on the restrained shrinkage testing apparatus and instrumentation. We also want to thank Mr. Silas Shields, Kristina Milaj and Nick Breisach for their help as undergraduate research assistants. We would especially like to thank Mr. Manfred Dittrich. Without his incredible machining experience much of this work would have not been possible to be completed with such attention to detail in our testing apparatus. He is an invaluable member of the team.

Executive Summary

Early-age bridge deck cracking is a major concern for many DOTs throughout the United States and specifically those in the Pacific Northwest. Cracking within the first months of a bridge deck's lifespan severely hinder its long-term performance and durability ultimately reducing the sustainability of this crucial piece of transportation infrastructure. Increased maintenance costs, driver interruptions and possible damage to bridge structure are also a result. This is a specific problem that the Oregon DOT has experienced and is trying to find solutions to reduce or eliminate related cracking. The incorporation of blended sizes of synthetic fibers could provide resistance to shrinkage-related cracking in addition to other benefits such as increased resistance to surface wearing and ultimately reduce maintenance costs and provide longer lasting more sustainable bridge decks. The extension of the proposed research to other types of paving surfaces, e.g. rigid concrete pavements to resist cracking is a possible broader impact.

It has been established that fibers of uniform size (nominally 1" or greater) can increase fracture toughness and ductility of concrete, reduce the potential for cracking and if cracking occurs, reduce crack widths and lengths. (Folliard et al., 2006) Smaller fibrillated (micro-fibers) have also shown benefits for reducing plastic shrinkage cracking when concrete is still in the fresh state. However, blending fibers of different sizes, both length, thickness and composition, to improve performance has not been thoroughly investigated and is thus not well understood. The potential for reduction in cracking exists, as evidenced by a recently constructed concrete bridge deck - Willamette River Bridge on I-5 in Eugene, OR. This bridge deck experienced significant cracking without fibers for spans 1, 2 and 4-9. These deck sections required crack sealing after construction resulting in increased construction costs and delays in opening the bridge to the public. Span 3, however, was constructed with a fiber blend (mixed fiber size and type), and to date no cracking has been observed and thus no crack sealing was needed.

The major findings from this research were:

- The incorporation of fibers at three different dosage rates: 5 lb/yd^3, 7.5 lb/yd^3 and 10 lb/yd^3, had a minimal impact on the 90-day drying shrinkage of high performance concrete specimens, compared to the control. These specimens were wet cured for 14 or 28 days prior to initiation of drying.
- The incorporation of fibers at three different dosage rates: 5 lb/yd^3, 7.5 lb/yd^3 and 10 lb/yd^3, showed a slightly increased amount 90-day drying shrinkage of high performance concrete specimens, compared to the control. These specimens were wet cured for only 3 days prior to initiation of drying.
- The incorporation of fibers into high performance concrete (HPC) increased the time-to-cracking in restrained ring testing over the HPC control and also markedly changed the post-crack behavior of the concrete indicating the fiber's ability to limit the propagation of cracks once they start forming.
- In restrained ring testing the HPC control mixtures showed average crack widths of 0.035 in. in width. In all mixtures containing fibers, the crack widths were significantly reduced to 0.005-0.008 in.

Based on the results of this research project the incorporation of fibers into high performance concrete mixtures should reduce the potential for both early and later-age cracking for ODOT bridge decks. The results support that the incorporation of fibers should also help to control crack widths even if cracking does occur in the HPC. Importantly the use of fibers did not impact either freeze-thaw performance or chloride ion penetrability of the mixtures investigated in this study. In fact the incorporation of fibers may further improve the freeze-thaw resistance of HPC. In terms of fiber dosage rates, all those investigated improved concrete properties in terms of cracking resistance. At the higher fiber dosage rate of 10 lb/yd^3 there were marked decreases in concrete workability. These were overcome with increasing dosages of superplasticizer. However, it is not expected that this high of a dosage rate of fibers will provide such significant improvement in performance that the higher dosage rate is justified. Therefore, a dosage rate of 5 lb/yd^3 or 7.5 lb/yd^3 are recommended. These dosage rates may be further modified based on the results of current and/or future HPC decks that incorporate fibers.

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1.0 Introduction

1.1 Project Background

Early-age bridge deck cracking is a major concern for many DOTs throughout the United States and specifically those in the Pacific Northwest. Cracking within the first months of a bridge deck's lifespan severely hinder its long-term performance and durability ultimately reducing the sustainability of this crucial piece of transportation infrastructure. Increased maintenance costs, driver interruptions and possible damage to bridge structure are also a result. This is a specific problem that the Oregon DOT has experienced and is trying to find solutions to reduce or eliminate related cracking. The incorporation of blended sizes of synthetic fibers could provide resistance to shrinkage-related cracking in addition to other benefits such as increased resistance to surface wearing and ultimately reduce maintenance costs and provide longer lasting more sustainable bridge decks. The extension of the proposed research to other types of paving surfaces, e.g. rigid concrete pavements to resist cracking is a possible broader impact.

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DOTs need additional tools to reduce (if not eliminate) cracking risk of bridge decks. (Brown et al., 2006) Fiber incorporation into concrete has been shown to provide increased durability, but investigations into mixed fiber sizes have not been conducted. Additionally, specifications with clear guidance need to be developed when fibers are an option for improving concrete performance. The goal of this project is to investigate the potential for mixed fiber blends to reduce shrinkage and ultimately cracking in high performance concrete. Recommendations for dosage rates of mixed fiber blends will be provided to aid in specification development.

2.0 Literature Review: Recent DOT Research On Synthetic Fibers

Fiber-reinforced concrete (FRC) is concrete containing fibers to increase its structural integrity. Fiber types may include steel, synthetic, glass and natural fibers. Only synthetic polypropylene fibers were considered in this project. Polypropylene is a thermoplastic polymer used in a wide variety of applications including packaging, textiles and rope among others.. Like most polymer based materials polypropylene is resistant to chemicals and fatigue. Manufacturers make two types of fiber, which include macro-synthetic and micro synthetic, often referred as type 1 and type 2 synthetic fibers respectively. Macro-synthetic fibers are also often referred to as structural fibers since they are used to carry load. These fibers range from 1”-2” in length and have a young’s modulus between 725-1450 ksi (5-10 GPa). Micro-synthetic fibers are mainly used for early age cracking (plastic shrinkage cracking), range from 0.25”-1” in length and have a young’s modulus of 435-725 ksi (3-5 GPa). According to manufacturers, the use of polypropylene fibers will reduce plastic shrinkage cracking, improve shatter, impact and abrasion resistance, and reduce damage from freeze/thaw attack. Manufacturer dosage rates vary but most suggest a minimum 3lb/yd^3 of concrete. Researchers present dosage rates as a percentage of concrete volume, usually between 0 and 0.75%. Although many of these benefits may be true, the main focus is to determine if the use of synthetic fiber blends will increase cracking resistance in HPC.

In addition to the benefits claimed by manufacturers, one of the material properties with most significant improvement is toughness. Toughness is the ability for a material to absorb energy and plastically deform without fracturing. Plain concrete is a brittle material, and when loaded to fracture does not continue to carry load or deflect. FRC is able to continue to carry load and deflect after it has reached its fracture strength. Although toughness is a desirable property for any structural material it is not related to any parameters used in structural design. However, the dynamic performance of concrete in structural elements (pavements, bridge-decks, slabs etc.) is critical therefore; the use of FRC is easily justified.

Polypropylene fibers have been used in concrete mainly for plastic shrinkage control, however; field results have shown improved cracking resistance. This has recently sparked further interest for the use of fibers in HPC where cracking affects the durability of concrete structures. Kovler et al. stated that the inclusion of polypropylene fibers was highly effective in reducing plastic shrinkage (1992). Fiber reinforcement made of steel and or artificially affects the ductility, the width of cracks and the rheological characteristics of composites (Saje et al., 2011). In addition, the geometry of these fibers influences the bond between the fibers and the concrete matrix (Saje et al., 2011). According to Banthia and Gupta, the use of polypropylene fibers generally results in the decrease of crack width and number of cracks and thinner smaller fibers are more effective than longer and thicker fibers (2006).

The mitigation of drying shrinkage related cracking may be expected; however, researchers have mixed results about the effect polypropylene fibers have on shrinkage reduction. Saje et al. found that HPC with polypropylene fibers reduced the overall autogenous and drying shrinkage when compared to plain HPC (2006). With regards to total shrinkage Kovler et al. stated that there was no significant reduction up to a volumetric content of 0.2% (1992). Aly et al. concluded that the use of polypropylene fibers in normal strength concrete at a 0.50% by volume dosage rate increased shrinkage by as much as 22% when compared to concrete containing no fiber (2005). Myers et al. mentioned that polypropylene fibers exert a very small influence on shrinkage (2008). Although many researchers are in disagreement, all agree that polypropylene fibers provide crack resistance, which is observed mainly in the number and width of the cracks. Much of the research was done with micro-synthetic fiber, which may be due to the findings from Banthia and Gupta in their fiber geometry study.

Although there is an ongoing debate whether fibers increase or reduce shrinkage most researchers agree that synthetic fibers do control cracking. However, there is a lack of research using both macro-synthetic and micro-synthetic fibers in a blended system.

2.1 Florida Department of transportation (FDOT)

The Florida DOT investigated four types of fiber that included polypropylene, PVA (polyvinyl alcohol), steel and cellulose in Florida environmental conditions. The project was titled, "Durability of fiber reinforced concrete in Florida environments" and authored by Roque et al. (2009). The exposure conditions were salt water (immersed and wet/dry) and swamp (acid) for

27 months. All beams were moist cured for 14 days prior to exposure. Beams were cast to determine residual strength testing according to ASTM C1399 and flexural performance testing according to ASTM C1609. Theoretically based on these two tests they would be able to identify the cracking resistance during their exposure conditions. Although their testing methods differ from this project their observations and results are important since they worked with polypropylene fibers and identified which fiber type has higher cracking resisting performance. The steel fiber had the strongest resistance to crack propagation in limewater immersion due to the excellent bonding with the matrix (Roque et al., 2009). However, the steel fibers corroded in immersed saltwater and during cyclic wetting and drying cycles. The PVA fibers were the weakest due to their poor resistance to saltwater which caused them to degrade over time. The polypropylene fibers exhibited good performance in all environments due to their inherent resistance to chemicals and shrinkage effects. Cellulose fiber results were not included as problems with fiber dispersion affected the outcomes. Work performed at Oregon State University on a separate project has addressed the fiber dispersion issue. Also, according to Roque et al.:

> Effect of fibers on cracking resistance could not be assessed based on the test results from either average residual strength (ASTM C1399) or flexural performance (ASTM C1609). It was determined that the conventional beam approach resulted in non-uniform degradation and stress/strain distributions through the cross-section. Also, beam tests generally resulted in multiple cracks initiating at the bottom of the specimen and instability subsequent to matrix cracking. These critical factors significantly affected pull-out mechanism of fibers and disturbed the evaluation of failure during post-cracking (Roque et al., 2009).

Due to the difficulties with their test set ups Florida DOT was not able to clearly identify the cracking resistance of each fiber type. However, they do make interesting observations about polypropylene fibers that achieved higher performance in the most aggressive exposure conditions.

2.2 Oregon Department of Transportation (ODOT)

In 1997 ODOT overlaid the Link River Bridge with microsilica (silica fume) concrete, reinforced with polypropylene fibers. Two years later an inspection was made by Eric W. Brooks, who reported the findings in 2000. According to the fiber manufacturer plastic shrinkage and settlement cracking would be reduced during the early life of the concrete as well as the formation of intrinsic cracking. Only the Northbound lane contained fiber yet the result was similar for both lanes. According to Brooks, cracking resistance was found to be no better in the northbound lane with fibers, compared to the southbound lane without fibers.

2.3 Texas Department of Transportation (TXDOT)

Folliard et al. studied the use of fiber in continuously reinforced concrete pavements (CRCP) (2006). One of the major concerns in this study was concrete spalling due to the poor performance of siliceous river gravel. According to Folliard et al., pavements constructed in the winter experienced the most severe cases of spalling, which were caused by induced cracks in the upper portion of the slab due to the low temperature gradient (2006). As the temperature increased the cracks propagated further into the slab and the way the crack propagated was dependent on the aggregate type. Folliard explained that in river gravel the cracks tend to travel around the aggregate due to a weaker bond to the cement paste (2006). In addition, according to Dossey and McColluogh, field performance in Texas has shown that pavements constructed with limestone aggregates generally perform better with respect to spalling than those constructed with siliceous river gravel (1999). This is due to a stronger bond between the limestone and the paste, which encourages the cracks to propagate directly through the aggregate (Folliard et al., 2006).

To mitigate spalling the inclusion of fibers was evaluated both in the laboratory and in the field. Two steel fiber (corrugated and hooked end) and two micro-synthetic fibers (monofilament and fibrillated) were used. Flexural toughness was the only hardened property that was significantly affected by the addition of fibers. This was specifically important to this project due to the spalling concerns with existing CRCP in Texas. According to Folliard et al., “Steel fibers typically provide greater improvements in toughness and residual strength than synthetic fibers, and both parameters are proportional to dosage rate for any fiber used”, in addition “toughness and residual strength should be good indicators of improved spalling performance of CRCP, but field evaluations of CRCP containing fibers will be critical for verifying this hypothesized correlation” (2006). During the time allotted to this research project there was no significant cracking and unfortunately the field performance of fibers was not fully evaluated. No significant improvement in cracking resistance was observed due to the age of the concrete during field monitoring.

2.4 Virginia DOT

Dr. Celik Ozyildirim studied high performance fiber-reinforced concrete for the bridge deck application. This project covered both field monitoring and laboratory testing. A bridge deck was placed on steel beams over 4 piers on Route 11 over the Maury River in Lexington, Virginia. Control sections were cast on the same deck and were monitored over a 5-year period. Synthetic fibers were used at a dosage rate of 8.75 lb/yd^3 and the HPC was air entrained to achieve 6.5% air. In the laboratory dosage rates of fiber of 5-15lb/yd^3 were used and air contents of 2.6-10%

were recorded. It was immediately noticed that only 2 batches were on target (5.1% and 6.4%). The batch with 10% air did not meet 28-day strength requirements (4000 psi). Permeability was also tested, however there was no mention of the standard used, and all batches meet the minimum charge passed (2500 coulombs) requirement. Testing according to ASTM C 1399 showed that increasing the fiber dosage also significantly increased the residual strength. Although there were differences between the batches used in the laboratory and those produced in the field, the addition of fibers showed similar results. Synthetic fibers provided higher residual strength and controlled cracking. According to Ozyildirim, the following conclusions where observed:

- Adding fibers provides residual strength and controls cracking. There were fewer and narrower cracks in the FRC even though the FRC had more shrinkage than the control. The residual strength is directly proportional to the fiber content.
- Controlling deflection through the actuator or the beam affects residual strength. The residual strengths were higher when the rate of deflection was controlled through the actuator.
- Adding fibers decreases workability.
- Pumping in a vertically downward direction reduces the air content and slump of freshly mixed concrete. However, concretes with reduced air content can provide satisfactory resistance to freezing and thawing if a satisfactory air void system is maintained.

- Differences in slump and air content were observed before and after pumping depending on the location of the sample.
- The permeability of FRC is comparable to that of conventional concrete. (Ozyildirim, 2005)

Like other researchers Ozyildirim found that cracking control was one of the most significant improvements. Also, similar to the problems observed at FDOT, the residual strength test according to ASTM C 1399 was not ideal.

2.5 Summary

Researchers from DOT's and academic journals all found that polypropylene fibers control cracking. Shrinkage reduction is still being debated and some researchers have found that polypropylene fibers either increased or reduced total shrinkage. There has not been a major study where blended synthetic fibers are used. Generally only macro or micro synthetic fibers are used but regardless of fiber type fewer cracks were observed in both laboratory and field. The main test being used to assess cracking risk was the residual strength test, but there were noted concerns with this method due to instability and deflection. The inclusion of synthetic fibers results in lower concrete workability. In extreme durability conditions polypropylene were superior to all other fibers (steel, PVA, and cellulose) due to their inherent anticorrosive and chemical resistant properties.

3.0 Experimental Methods and Materials

3.1 Materials

3.1.1 Cementitious Materials

The cementitious materials used in this research project included an ASTM C150 Type I/II ordinary portland cement (OPC), ASTM C618 Class F fly ash, ASTM C 989 Ground Granulated Blast-Furnace Slag. These materials were manufactured by Lafarge North America. An ASTM C 1240 silica fume, Rheomac 100 manufactured by BASF was also used.

Table 3.1: Oxide Analysis (wt %)

Oxide	OPC	Class F Fly Ash	Slag	Silica Fume
CaO	63.57	10.20	30-50	-
SiO_2	19.95	55.24	-	60-100
Al_2O_3	4.71	15.77	-	-
Fe_2O_3	3.50	3.64	-	-
MgO	0.85	3.64	0-20	-
Na_2O	0.25	2.08	-	-
K_2O	0.27	2.08	-	-
TiO_2	0.24	0.94	-	-
MnO_2	0.09	0.12	-	-
P_2O_5	0.09	0.23	-	-
SrO	0.16	0.32	-	-
BaO	0.06	0.62	-	-
SO_3	3.19	0.70	-	-
Total Alkalis as Na_2O	0.43	-	-	-
Loss on Ignition	3.19	0.23	-	-

**Oxide analysis of slag and silica fume was taken from the manufacture

3.1.2 Admixtures

An ASTM C494 Type F polycarboxolate-based high-range water reducer (ADVA Flex®) supplied by Grace Construction Products was used to achieve consistent workability (target 3-5 in slump). An air-entraining admixture (DARAVAIR® 1000) supplied by Grace Construction Products was also added to achieve a target air content of 6 ± 1.5% to ensure proper freeze/thaw resistance. Fresh concrete temperature was measured at the end of each mixture using an infrared thermometer.

3.1.3 Aggregates

The coarse and fine aggregate used in this study were from one local source. The local aggregate was siliceous river gravel and river sand. The crushed aggregate used in this study to investigate the effect of aggregate angularity was from the same source and had similar aggregate properties with the only difference being crushed rather than predominantly rounded surface texture.

3.1.4 Fibers

Propex Novamesh 950® fibers were used as the synthetic fiber blend. Shown below in Table 3.2: Synthetic fiber material propertiesare the physical and chemical components of each fiber type. As previously mentioned, micro-synthetic are the smaller fibrillated fibers and macro-synthetic are the coarser longer fibers.

Table 3.2: Synthetic fiber material properties

	Micro-Synthetic	**Macro-Synthetic**
Material	Polypropylene	Coarse Macro-Monofilament Polypropylene
Absorption	None	None

Specific Gravity	0.91	0.91
Fiber Length (in)	0.5	1.8
Fiber Diameter	-	0.33 Nominal
Electrical Conductivity	Low	Low
Melting Point (°F)	324	328

The application rate suggested by the manufacturer is a minimum of 5 lb/yd^3 of concrete where 85% of fibers by weight are macro-synthetic and 15% are micro-synthetic (pre-mixed by the manufacturer). No modifications to the weight percentages were made. In addition, fibers were added directly into each concrete mixture without mixture design modifications as specified by the manufacturer. Only super plasticizer dosages were modified to insure good workability (3-5 in slump).

3.1.5 Mechanical Properties Test and Curing Conditions

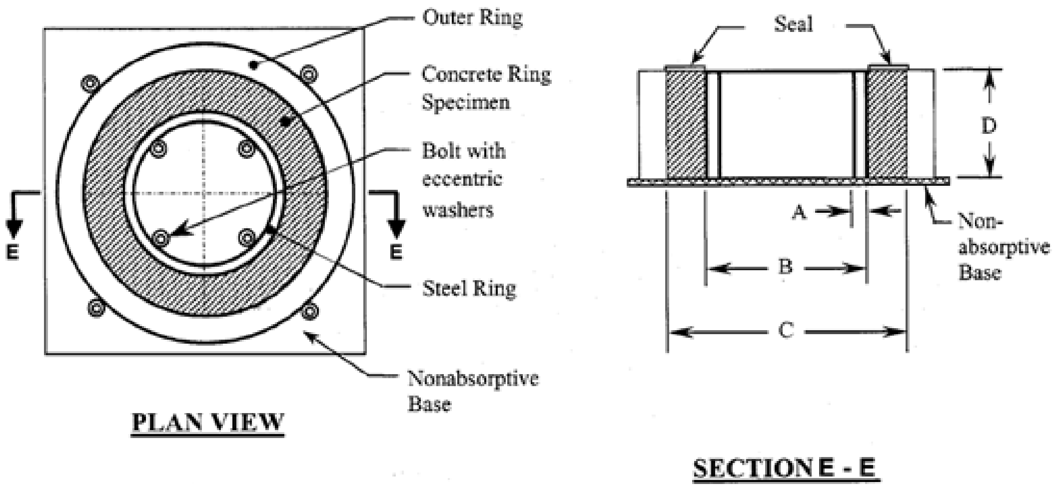
Mechanical properties were tested for each mixture at 7, 14 and 28 days age, including compressive strength (ASTM C39), splitting tensile strength (ASTM C496), and modulus of elasticity (ASTM C469). For each mixture, $\phi 4 \times 8$ in cylindrical samples were cured in two conditions: standard 28-day wet cure, and 28-day matched cure. For standard curing, samples were demolded 24 hours after casting and stored in an ASTM C 511 standard moisture room (23°C and 100% RH) until testing. For matched curing, samples were demoded 24 hours after casting and stored in the standard moisture room until the end of desired wet curing periods. Then these samples were moved to a drying environment (23°C and 50% RH) and stored near the specimens used for restrained cracking (ASTM C 1581). This was to ensure the measured mechanical properties were representative of ring specimens.

3.1.6 Free Shrinkage Test

Free drying shrinkage was monitored using the ASTM C157 test, which is a common method to determine length change of hardened concrete prisms (3 × 3 × 11.25 in). The specimens were de-molded 24 hours after concrete mixing and placing. The specimens were then stored in an ASTM C 511 moist room (23 ± 2°C and >95% RH) until desired curing duration (i.e. 3, 14 and 28 days in this study). Upon the end of curing duration, the specimens were moved into a drying environment (23 ± 2°C and 50 ± 4 % RH). During drying, the length was monitored by a comparator. The mass change was also recorded during the testing period.

3.1.7 Restrained Shrinkage Test

The restrained shrinkage ring test has been frequently used as a testing technique to identify potential cracking risk of concrete and mortar mixtures. There are two standard testing procedures based on similar principles. The major difference is the concrete thickness, where ASTM C1581 uses 1.5 in, and AASHTO T334 specifies 3 in (ASTM, 2009 and AASHTO, 2008). Compared to the standard testing procedure, several modifications were applied in this project: 1) to achieve more accurate cracking evaluation, three rings instead of two were tested for each mixture; 2) a specific curing duration (14 days) was used to stimulate field curing conditions; 3) mechanical properties at 28 day age were tested on match cured cylinders. Figure 3.1 below shows the dimensions and components of both the ASTM and AASHTO ring apparatus.



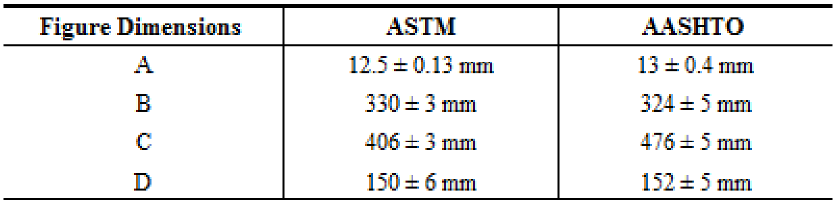


Figure Dimensions	ASTM	AASHTO
A	12.5 ± 0.13 mm	13 ± 0.4 mm
B	330 ± 3 mm	324 ± 5 mm
C	406 ± 3 mm	476 ± 5 mm
D	150 ± 6 mm	152 ± 5 mm

Figure 3.1: Dimension of rings test setup (ASTM, 2009)

A sample of freshly mixed concrete was compacted in a circular mold around the steel ring. The compressive strain developed in the steel ring caused by initial hydration, curing and restrained shrinkage of the specimen under drying were measured from the time of casting. The curing environment allowed the specimens to be moist cured using wet burlap covered with a polyethylene film for at least 24 h at 23.0 ±2.0 °C. The outer ring was removed at 24 h and wet curing using saturated burlap was done until the end of the desired curing duration. During the curing process, the burlap was re-wetted as necessary to maintain 100% RH environment for the concrete. At the end of the curing process, the burlap was removed and the top surface of the specimen was sealed with silicone sealant to allow for drying only in the horizontal direction. The strain gauge reading was monitored and recorded every 5 minutes until all 3 rings had shown visible cracking along the height of the ring.

Figure 3.2 shows a typical strain gauge reading from the time the concrete was initially cast, through the peak heat of hydration, during wet curing and then exposure to the drying environment followed by cracking.

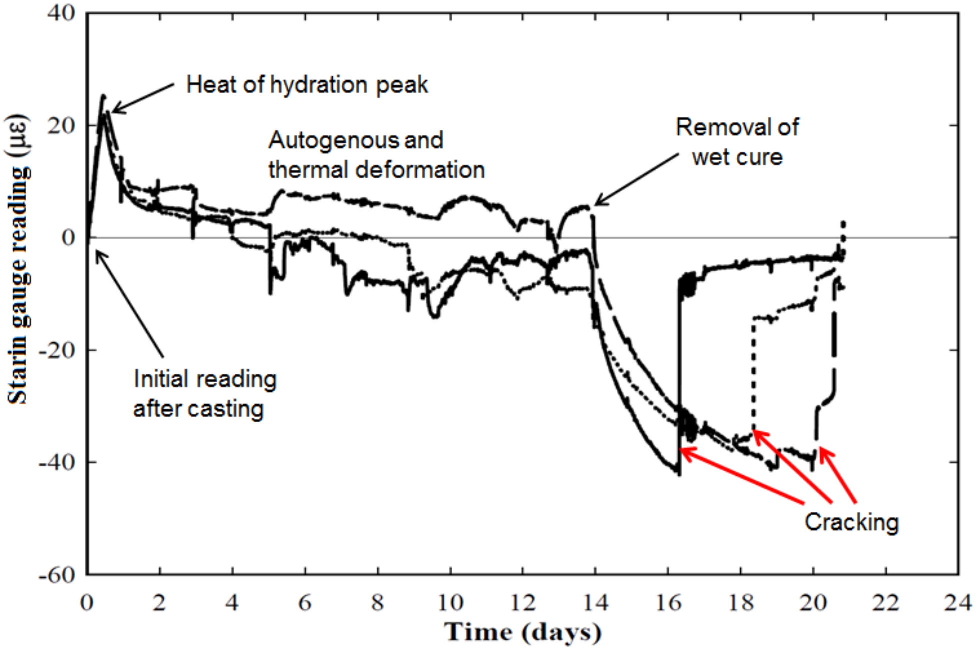
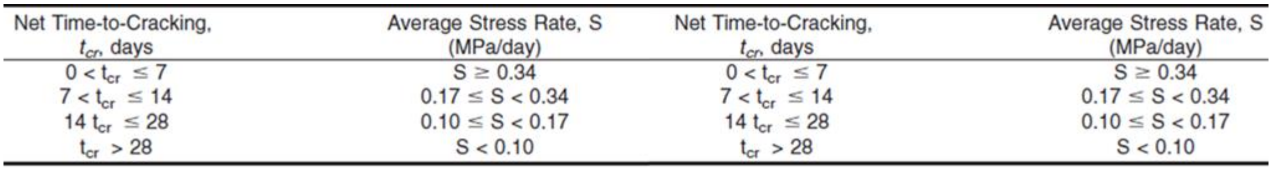


Figure 3.2: A typical averaged strain gauge reading in ring tests (3 replicates) (Fu, 2013).

The strain gauge reading was recorded right after the specimens were cast and moved into the environmental chamber. It can be seen in

Figure 3.2 that the steel ring first showed registered expansive strain due to the heat released from hydration of the concrete. After the removal of the outer mold (24hrs from casting), the concrete ring specimens were cured by wet cured using burlap until the end of the desired curing duration. During this period, some of the compressive strain in the steel ring was offset by the tensile strain generated due to autogenous shrinkage. Some noise in the strain gauge reading was also recorded during this this period, which was believed to be due to the temperature and/or moisture variation within the sample. Once the burlap was removed the compressive strain due to drying and subsequent shrinkage of the concrete was observed. During the drying phase, a sharp jump in the strain gauge reading toward zero indicated cracking in the concrete. The time between exposure to drying and cracking is called time-to-cracking (days), which is an important parameter to evaluate the cracking resistance of the tested concrete. According to the strain gauge reading, an averaged stress rate (psi/day) in the concrete can be calculated, and used as another parameter in cracking risk evaluation. The cracking potential was evaluated based on Table 3.3 below.

Table 3.3: Potential for cracking classification (ASTM, 2009)



Net Time-to-Cracking, t_{cr}, days	Average Stress Rate, S (MPa/day)	Net Time-to-Cracking, t_{cr}, days	Average Stress Rate, S (MPa/day)
$0 < t_{cr} \leq 7$	$S \geq 0.34$	$0 < t_{cr} \leq 7$	$S \geq 0.34$
$7 < t_{cr} \leq 14$	$0.17 \leq S < 0.34$	$7 < t_{cr} \leq 14$	$0.17 \leq S < 0.34$
$14\ t_{cr} \leq 28$	$0.10 \leq S < 0.17$	$14\ t_{cr} \leq 28$	$0.10 \leq S < 0.17$
$t_{cr} > 28$	$S < 0.10$	$t_{cr} > 28$	$S < 0.10$

3.1.8 Freeze/Thaw Testing

ASTM C666 was used to determine the resistance of concrete to freezing and thawing cycles. This test method can be performed in two different ways. In Procedure A, the concrete is subjected to rapid freezing and thawing in water. In Procedure B, the concrete is subjected to rapid freezing in air and rapid thawing in water. These two procedures both determine the effects of variations in proportions, curing and soundness of the aggregates. The low temperature of the freeze cycle is -17.8 ^{o}C (0 ^{o}F) and the target thaw temperature is 4.4 ^{o}C (40 ^{o}F). Procedure A was used to assess the freeze/thaw performance of concrete with synthetic blended fibers.

Test specimens are cast according to ASTM C192, and demolded at an age of 24 +/- ½ hour after initial contact. Specimen dimensions were 3”x4”x16” rectangular beams. The specimens were then allowed to cure for 28 days. Upon completion of curing, the specimens were cooled to a temperature within ±2 ^{o}F of the target thaw temperature. The specimens were protected from moisture loss during the cooling until the freeze-thaw testing begins. Prior to the initial cycle, the mass and initial fundamental transverse frequency was measured. ASTM C215 outlines the procedures for determining the fundamental transverse frequency. Once freeze-thaw cycles have begun, the specimens were tested for fundamental transverse frequency and the mass recorded during the thawed condition. The fundamental transverse frequency was recorded every 36 cycles. The specimens were placed back in the chamber either randomly or in a predetermined rotation to ensure that the specimens are subjected to all conditions throughout the chamber. The test was continued until the specimens were subjected to either 300 cycles or their relative dynamic modulus had reached 60% of the initial modulus. The relative dynamic modulus was then calculated by the following equation:

$$P_c = (n_1^2/n^2) \text{ x } 100$$

Where:

P_c = relative dynamic modulus, after *c* cycles of freezing and thawing, percent,

n = fundamental transverse frequency at 0 cycles of freezing and thawing,

n_1 = fundamental transverse frequency after *c* cycles of freezing and thawing.

3.1.9 Rapid Chloride Permeability Test

ASTM C1202, or most commonly known as the rapid chloride permeability test (RCPT), was used to determine the concrete’s ability to resist chloride ion penetration This rapid test method determines the electrical conductance of concrete to determine the ability of concrete to resist the penetration of chlorides. A constant potential difference of 60 V was applied to the ends of the specimen. One end is immersed in a 3% sodium chloride solution, while the other end is immersed in a 0.3 N sodium hydroxide solution. The total charge passed through a 2in (50 mm) thick, 4in (100 mm) diameter piece of concrete during a 6-hour period provided an indication of the permeability. The sample age may have a significant effect on the results, for consistency all samples were wet cured for 56 days. Typically, in most concrete, the permeability becomes less if the sample is properly cured.

At the desired duration of curing, 2in (50 mm) thick slices of concrete were cut using a water-cooled diamond saw, and the specimens are conditioned for testing. The specimens were allowed to air dry for at least 1 hour before applying a rapid setting (approx. 1-3 hrs) sealant on the sides of each specimen. After the sealant set, the specimens were placed in a vacuum desiccator with all surfaces exposed. Once all specimens were in the desiccator, a vacuum pump was started, and a pressure of less than 0.039 in. (1mm) Hg was maintained for 3 hours. While the vacuum pump was still running, de-aerated water was introduced through a stopcock. Once the specimens were submerged, the stopcock was closed, and the vacuum was applied for 1 more hour. At the end of the 4 hour conditioning, air is allowed re-enter the desiccator, and the specimens soaked in this condition for 18 +/- 2 hours.

After completing the conditioning, the specimens were removed from the desiccator and excess water was removed. A circular vulcanized rubber gasket is placed on each half of the test cell and the halves were bolted together. The side filled with 3% NaCl solution and was connected to the negative side of the power supply. The other side (filled with 0.3N NaOH solution) was connected to the positive side of the power supply. The power supply was turned on, the voltage was set to 60.0 +/- 0.1 V, and the initial current was recorded. The current was recorded at least every 30 minutes for 6 hours. The test was terminated after 6 hours, unless the temperature of the solutions reaches 190 °F (88 °C). If the solutions exceed this temperature, boiling of the solutions or damage to the cell may occur. To determine the total charge passed during the six hour period, the following equation was used:

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{300} + 2I_{330} + I_{360})$$

Where:

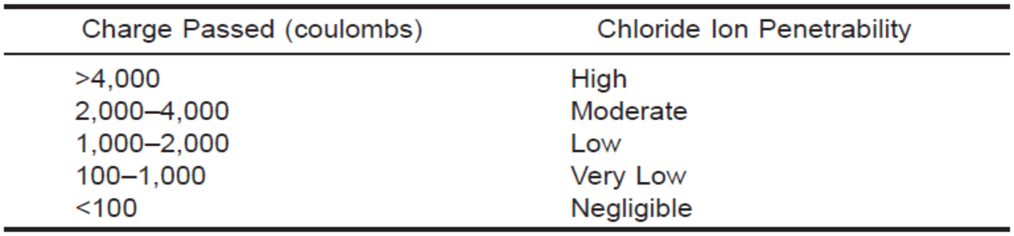
Q = charge passed, coulombs,

I_0 = current immediately after voltage is applied, amperes,

I_t = current at t min after voltage is applied, amperes.

To increase the accuracy of this test the current was recorded every second during the 6-hour test duration using a data acquisition system (DAS). Upon completion of the test the current was plotted over time. To calculate the total charge passed in coulombs the current-time curve was integrated. Using the DAS data was the preferred method of analysis; however, manual recordings were still taken in the case of equipment malfunction. Table 3.4 from was used to evaluate the chloride ion penetrability in qualitative terms.

Table 3.4: Chloride ion penetrability based on charge passed (ASTM Standard C1202, 2010)



Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

However, issues have arisen with using ASTM C1202 for determining the chloride permeability. During testing, the conductivity of the specimen may change due to the migration of chloride and hydroxyl ions (Beaudoin et al., 2000). Furthermore, with the addition of some SCMs (e.g. silica fume) a false estimate of the chloride permeability may result (Feldman et al. 1999). In mixtures that have low porosity, overheating of the specimens may occur, causing the test to be ended prematurely (Adam, 2009). Although there is dispute to the accuracy of this test method, it is the acceptable test method for chloride permeability according to ODOT (ODOT 2008).

3.1.10 Summary

The focus of this project was to optimize the fiber dosage to achieve the best results in free shrinkage, cracking risk, and durability properties. For each mixture, the following tests were performed:

- 6 Cylinders (ϕ100 × 200 mm) for compressive strength (3 replicates), splitting tensile (2 replicates), and static modulus of elasticity (2 replicates) for 28 day wet cured condition;
- 6 Cylinders (ϕ100 × 200 mm) for compressive strength (3 replicates), splitting tensile (2 replicates), and static modulus of elasticity (2 replicates) for 28 day match cured condition (several mixtures did not test match cured cylinders);
- 3 ASTM C157 prisms for each of 3, 14 and 28 day curing durations;
- 3 ring specimens (ASTM C1581 or AASHTO T344).

It should be noted that the free shrinkage prisms and concrete in the restrained ring testing go through the same curing conditions. Durability testing (Freeze/thaw and RCPT) was only conducted on the best candidates based on shrinkage reduction and time duration in the ring test.

3.2 mixture design

All concrete mixtures in this project were based on a specific ODOT HPC mixture design for bridge decks. The target compressive strength was 5000 psi and the minimum strength was 4000 psi. A w/cm of 0.37 was used in all mixtures. The total cementitious materials content was 633 lb/yd^3, containing 30% class F fly ash or slag and 4% silica fume as mass replacement. The coarse and fine aggregate content were 1074 lb/yd^3 and 659 lb/yd^3 respectively for local materials. High range water reducer and air entraining admixture were adjusted to achieve similar workability and air content for all mixtures. This mixture design was used as the control. Modifications were made to this mixture design to include blended fibers at varying dosage levels. Other modifications included SCM replacement or the use of different coarse aggregates. Table 3.5 shows the detailed mixture proportions for each mixture.

Table 3.5 Concrete mixture proportioning

Mixture	Cement ((lb/yd^3)	Fly ash (lb/yd^3)	Slag (lb/yd^3)	Silica fume (lb/yd^3)	Water (lb/yd^3)	Coarse aggregate (lb/yd^3)	Sand (lb/yd^3)	Fiber Dosage (lb/yd^3)
HPC1	419	189	-	25	139	1074	659	0
HPC2	419	-	189	25	131	1074	659	0
FHPC D5	419	189	-	25	139	1074	659	5
FHPC D7.5	419	189	-	25	139	1074	659	7.5
FHPC D10	419	189	-	25	139	1074	659	10
LCM1	363	165	-	22	139	1074	659	0
LCM2	347	158	-	21	115	1005	771	0
OPC1	633	-	-	-	139	1074	659	0
OPC + FA	248	128	-	25	139	1074	659	0
OPC + SF	361	0	-	25	139	1074	659	0
CHPC	419	189	-	25	139	1074	659	0
F/T D7.5	419	189	-	25	139	1074	659	7.5
F/T D10	419	189	-	25	139	1074	659	10

Distinguished suffixes were used to identify each mixture. HPC represents a high performance concrete mixture. “HPC1” uses Class F Fly Ash and “HPC2” uses Slag. The number preceding identifies the control mixture it is associated with. The Suffix “F” represents fiber addition, and the suffix “D” represents the dosage followed by the rate in pounds per cubic yard (lb/yd^3). CHPC is a mixture using crushed local siliceous river aggregate. Two low cement mixtures (LCM1 and LCM2) are distinguished by their cement content shown in Table 3.3. In addition to the low cement investigation, mixtures using only OPC, OPC + FA, and OPC + SF were investigated to determine their shrinkage potential. Table 3.4 provides further details on each mixture.

Table 3.6 Mixtures for ring tests

Ring Type	Mixture ID	Coarse aggregate type	Fine aggregate type	w/cm	Curing duration (days)	Other descriptions
ASTM	HPC1	Local	Local	0.37	14	Control with Fly Ash ¾” MSA
	HPC2	Local	Local	0.37	14	Control with Slag ¾” MSA
	FHPC1 D5	Local	Local	0.37	14	¾” MSA
	FHPC D7.5	Local	Local	0.37	14	¾” MSA
	FHPC D10	Local	Local	0.37	14	¾” MSA
	CHPC	Local	Local	0.37	14	Crushed Local ¾” MSA
	LCM 1	Local	Local	0.37	14	Low Cement Content

					¾” MSA
LCM 2	Local	Local	0.37	14	Low Cement Content ¾” MSA
OPC1	Local	Local	0.37	14	¾” MSA
OPC + FA	Local	Local	0.37	14	¾” MSA
OPC +SF	Local	Local	0.37	14	¾” MSA

4.0 Results and Discussion

4.1 Fresh Properties

Table 4.1 shows the summary of fresh properties for all mixtures.

Table 4.1: Fresh Properties

Mixture ID	Slump (in)	Air content (%)	Unit Weight (lb/ft^3)	Temperature (°C)
HPC1	5.0	6.0	144	21
HPC2	3.0	6.0	142	22
FHPC1 D5	2.5	6.2	143	22
FHPC1 D7.5	5.5	7.0	140	24
FHPC D10	3.0	6.0	143	20
CHPC	3.3	7.5	139	22
LCM 525	2.5	6.6	140	24
LCM 550	3.8	8.0	135	24

OPC1	2.5	3.0	142	22
F/T D7.5	2.5	6.0	140	24
F/T D10	2	6.0	140	26

Only mixtures with target air entrainment were tested for restrained and free shrinkage. Mechanical properties Table 4.2 shows the summary of compressive strength, splitting tensile strength, and modulus of elasticity of all mixtures. Most mixtures were within the 4000psi minimum compressive strength. In addition to the standard 28-day curing regime, samples were exposed to the environmental chamber drying conditions after 14 days of wet curing. At 28 days they were tested to determine the “match cured” strength.

Table 4.2 Concrete Mechanical Properties

	28 Day, Wet Cured			28 Day, Match Cured		
Mixture ID	Compressive Strength (psi)	Tensile Strength (psi)	Modulus of Elasticity (ksi)	Compressive Strength (psi)	Tensile Strength (psi)	Modulus of Elasticity (psi)
HPC1	5126	588	4679	5787	638	4449
HPC2	4620	485	4190	-	-	-
FHPC1 D5	3930	462	3480	-	-	-
FHPC1 D7.5	4050	436	3910	5010	536	4110
FHPC1 D10	4090	520	3910	5180	511	4230
CHPC	3599	412	4103	3920	345	3793
LCM 525	3450	520	4100	-	-	-
LCM 550	2979	392	3590	3090	392	3470

OPC 1	6480	533	5260	6620	622	5400

Match cured mechanical properties were notably higher, roughly a 1000 psi increase, than the 28-day cured specimens. This was also noted in SPR 728 and is currently under investigation. It was initially predicted that adding fibers to the mixtures would result in lower mechanical properties due to the inherent paste replacement. In general, the inclusion of fibers reduced mechanical properties. However, all fiber mixtures were relatively close or within the 4000psi minimum. Additionally, the modulus of elasticity was lowered significantly, which indicated increased ductility. CHPC strengths were lower than expected. The lower strength may be due to the higher amount of air (7.5%), which is at the higher limit to ensure freeze/thaw protection. Also this mixture may require further optimization for aggregate particle size and appropriate paste content. This was the first usage of a crushed aggregate from this source (same as the rounded river gravel) and therefore further work may be necessary to ensure that this mixture meets ODOT requirements. OPC1 showed significantly higher mechanical properties. This was likely due to the absence of SCM’s, which can slow down the strength gain, compared to a 100% OPC mixture. As for mixtures with low-cement-content the mechanical properties notably decreased and do not meet ODOT strength requirements.

4.2 Free shrinkage

4.2.1 Blended Fiber Mixtures

Free drying shrinkage data of 3, 14, and 28 day curing durations was conducted for all synthetic blended fiber and control mixtures. All prisms were regularly monitored until the 90-day curing duration to achieve accurate, consistent and timely results. The 3-day cure free drying shrinkage results are shown below in Figure 4.1.

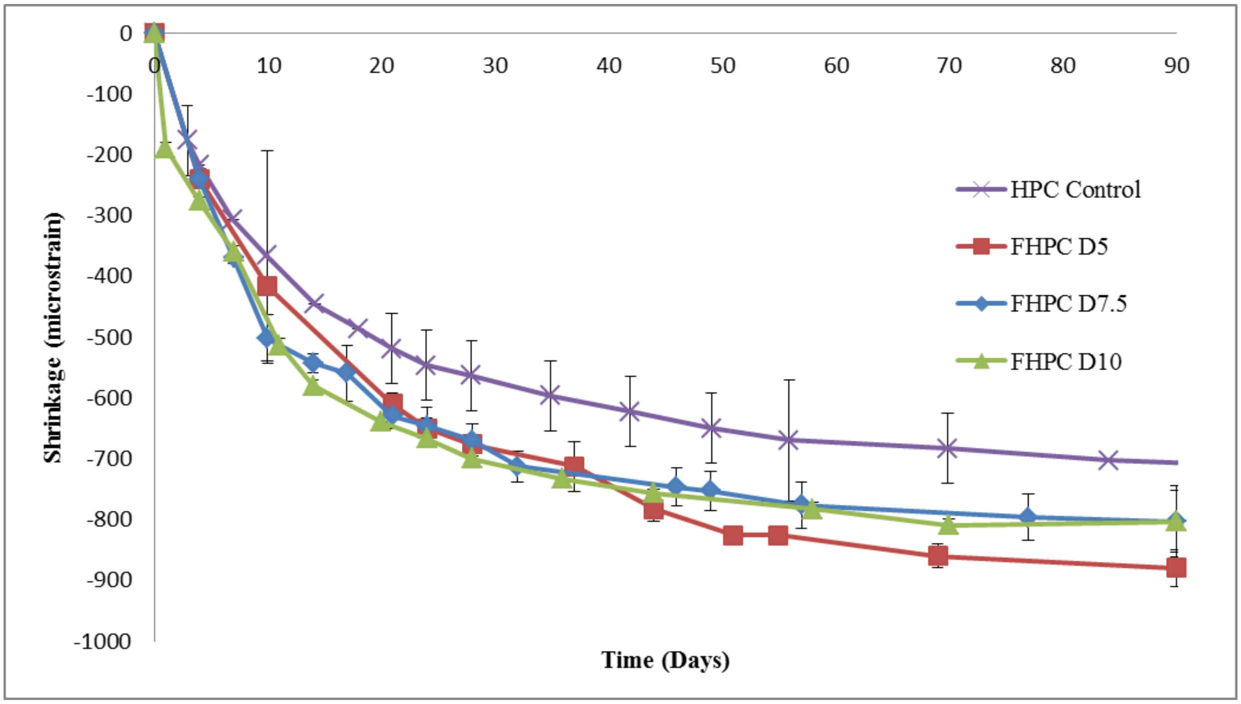


Figure 4.1: 3-day cure free drying shrinkage

The HPC control mixture clearly showed lower free shrinkage after the 3-day curing duration compared to the mixtures with fibers. The same correlation was found at the 14 and 28 day curing durations. However, the drying shrinkage in fiber mixtures progressively converged towards the control at the 14 and 28 day curing durations. This interaction is shown below in figures 4.2 and 4.3 below.

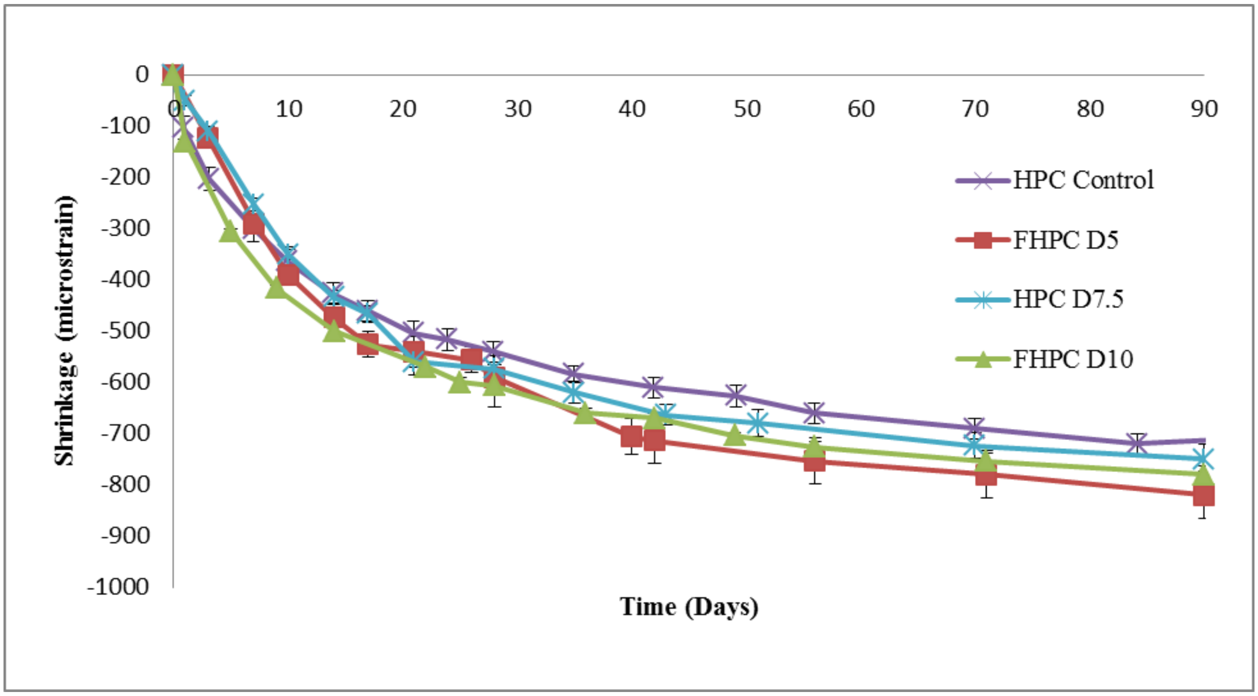


Figure 4.2: 14 day cure free drying shrinkage

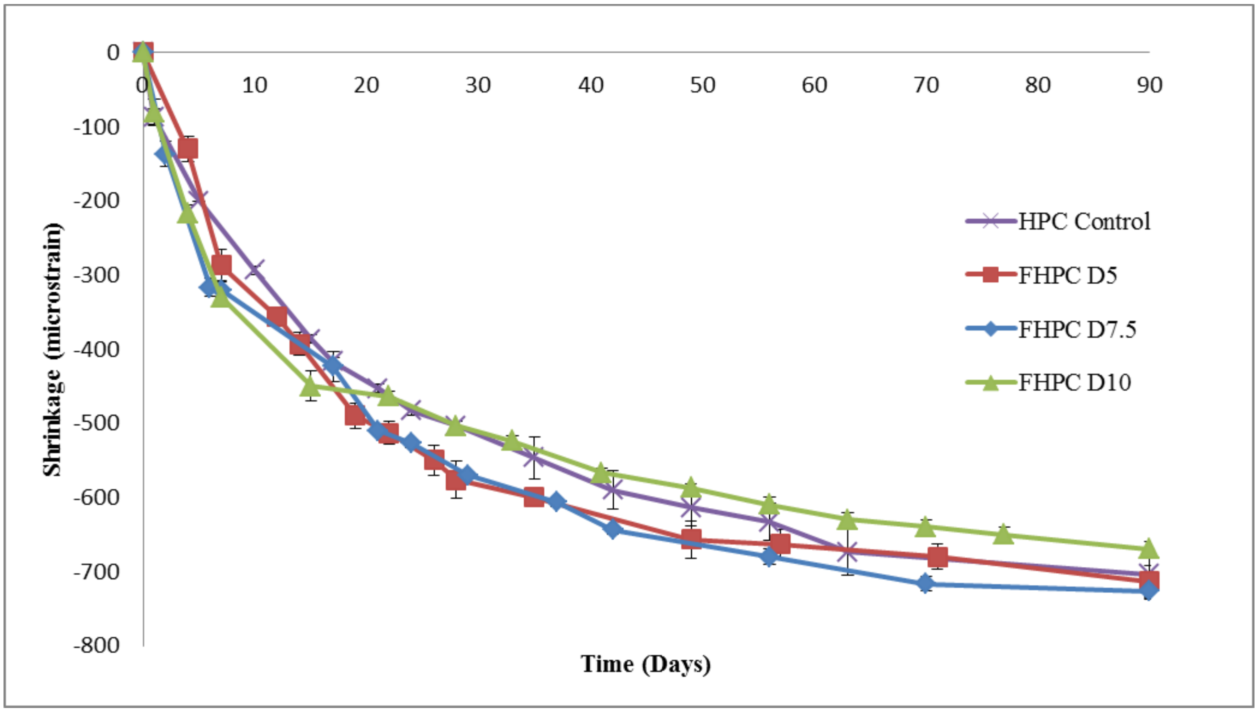


Figure 4.3: 28 day cure free drying shrinkage

The 14 and 28 day curing durations achieved similar drying shrinkage results. Only FHPC D5 showed higher shrinkage (820 micro-strain at 90days of drying) at the 14 day curing duration. However, when the specimens were cured for 28 days all specimens had similar drying shrinkage (roughly 700 micro-strain at 90 days of drying) and FHPC D10 showed the lowest shrinkage. There was no significant increase or decrease in drying shrinkage when using blended synthetic fibers in HPC.

Investigation to Reduce Drying Shrinkage

Modifications to the standard HPC mixture were made to study the effect of drying shrinkage. The effect of SCM's, and cement content on drying shrinkage was only studied at the 14 day curing duration. Specimens were monitored for 56 days to determine if lower drying shrinkage was achieved. Shown below in Figure 4.4 is the 14-day cure free drying shrinkage of various modified concrete mixtures.

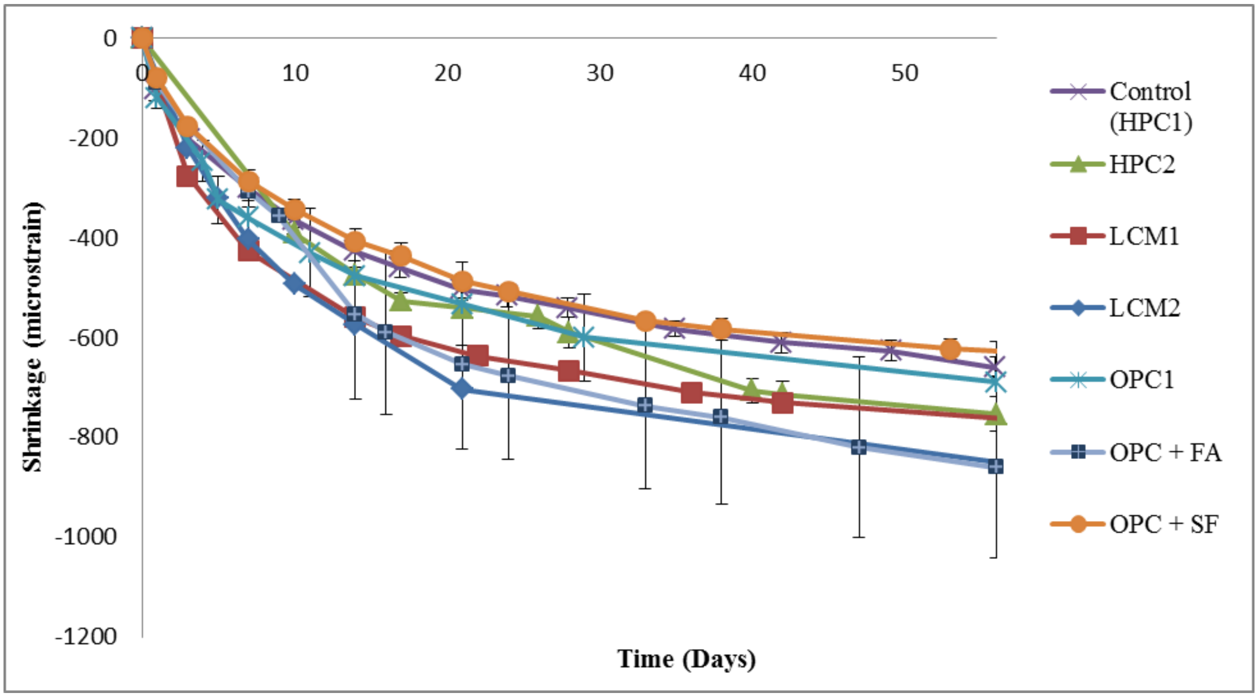


Figure 4.4: Free drying shrinkage of modified concrete mixtures

Although a low shrinkage mixture was not achieved during this study there are important findings for future research. First, the cement content in current HPC mixtures has been regarded as one of the most important factors for high shrinkage. Lowering the cement content to what is considered “low cement content” or (500-550lb/yd^3) should have provided a reduction in shrinkage. According to Darwin et al., a cement content of 540lb/yd^3 will limit the potential for shrinkage cracking and achieve moderate strength (2010). In addition, cracking occurs up to 3 times as much in concrete with strength of 6500psi when compared to concrete with 4500psi strength (Darwin, 2010). However, as shown above lowering the cement content was not successful. In addition, it did not meet the mechanical property requirements for ODOT bridge decks.

Second, the effect of SCM’s to the HPC mixture was one of the major findings. A mixture without any SCM’s (OPC1) was cast to identify the effect of the various SCMs when used as a percent replacement for the portland cement. The use of class F fly ash at a 30% replacement caused the highest amount of shrinkage and the use of silica fume at a 4% replacement had similar shrinkage behavior to the HPC control mixture. The use of slag at a 30% replacement showed lower drying shrinkage (about 100 microstrain) than using fly ash at 90 days. There is a synergistic effect when using OPC in conjunction with fly ash and silica fume, however; there may be room for improvement since fly ash notably increases drying shrinkage. Subramaniam et al., showed that mixtures with ultra-fine (mean particle size equal to 3µm) Class F fly ash showed higher drying shrinkage when compared to mixtures with plain OPC and OPC with silica fume (2005).

Restrained shrinkage

4.2.2 ASTM C1581

Table 4.3 provides a summary of the ASTM C1581 ring results, including time-to-cracking and the corresponding stress rate. Time-to-cracking is the time elapsed between initiation of drying and the cracking in the rings. Upon cracking, a sudden change will show in two or more strain gauges, which can also be confirmed by visual inspection. Stress rate at time-to-cracking was calculated according to ASTM C1581. Based on time-to-cracking or stress rate, a cracking potential can be assigned to each mixture based on the work by (See et al, 2004). When determining the cracking potential classification, high priority should be given to stress rate at cracking. On the one hand, the stress rate better quantifies the stress of the concrete, which is directly related to cracking potential. On the other hand, time-to-cracking is involved in stress rate calculation. In other words, stress rate indicates a more comprehensive evaluation. All individual strain gauge readings can be found in Appendix A.

Table 4.3 Summary of time-to-cracking and stress rate of ASTM ring tests

Mixture	Curing Duration (days)	Time-to-Cracking, (days)				Stress Rate, (psi/day)				Cracking Potential Classification*
		A	B	C	Ave.	A	B	C	Ave.	
HPC1	14	4.4	4.6	3.6	4.2	50	41	70	54	H
HPC2	14	6.2	6.2	8.2	6.9	47	48	40	45	MH
FHPC1 D5	14	5.9	5.9	4.9	5.6	64	45	56	55	H
FHPC1 D7.5	14	4.6	6.6	7.1	6.1	53	51	53	52	H
FHPC D10	14	7.3	7.9	8.0	7.7	49	54	56	53	MH

CHPC	14	-	5.7	-	5.7	37	31	37	35	MH
LCM2	14	6.1	3.4	5.2	4.9	87	78	64	76	H
OPC1	14	2.7	5.7	5.4	4.6	40	56	46	47	MH

* H – High; ML – Moderate High; ML – Moderate Low; L – Low.

The first notable result was the difference between HPC1 and HPC2. The average time to cracking of HPC 2 was about 3 days longer than HPC1. The main difference between these two mixtures was that HPC1 contains class F fly ash and HPC2 contains slag. The shrinkage investigation discussed in section 4.2.2 shows similar results, where the use of OPC and fly ash yielded the highest free shrinkage. Another important observation is the time-to-cracking of ring A for the FHPC D7.5 mixture. The time-to-cracking was notably lower than ring B and C, which obtained similar results. This mixture should be repeated to confirm the cracking potential. Although low cement content mixtures did not achieve mechanical property requirements one set of rings was cast to determine the cracking risk. The LCM2 mixture increased the time in the rings by roughly 1 day.

Time-to-cracking in fiber mixtures improved as higher amounts of fibers were added. The highest amount of fibers tested was at the 10lb/yd^3 dosage rate, which is double the manufacture's recommended dosage. Overall, there was a 29%, 37%, and 59% increase in time in the rings when applying synthetic blended fibers at a 5lb/yd^3, 7.5lb/yd^3, and 10lb/yd^3 dosage rate respectively (comparing to HPC1). However, the use of slag at a 30% replacement had a similar reduction in time-to-cracking compared to concrete with fibers.

4.2.3 Strain Behavior

One of the most significant observations is the strain after and before the time-to-cracking of each specimen. Typically, it was observed that in concrete with no fibers there was little to no variation in the data before the time-to-cracking, which is indicated by the sharp decrease in strain. In the control mixture (see Figure 4.5) there is some noise before the time-to-cracking, but not considerably. After the ring cracks there is also little to no noise, which means that the concrete no longer carries tension. The strain behavior is markedly different when fibers are added. Figure 4.6 below shows an example of this interaction. First, instead of an abrupt decrease in strain there is a gradual decrease with a considerable amount of noise. This is due to the synthetic fibers, which provide crack propagation resistance, as the compressive strain due to drying overcomes the tensile strength. In addition, after the specimens have cracked there is a more gradual reduction in stress rather than the sharp decrease observed in mixtures without fibers. This suggests that the fibers continue to provide cracking resistance after the ring has cracked. Another observation is that in rings incorporating fibers the crack width was further reduced compared to the control mixtures. This is further explained in section 4.3.3 Figures Figure 4.5 and Figure 4.6 below show the average strain data for each ring in the control mixture (HPC1) and the 5lb/yd^3 fiber dosage respectively.

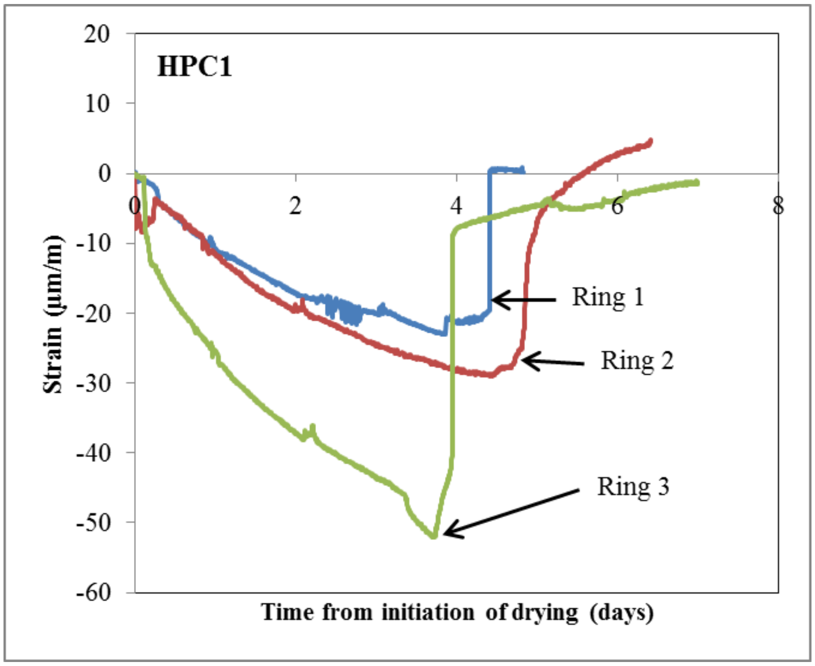


Figure 4.5: Restrained shrinkage strain data for control

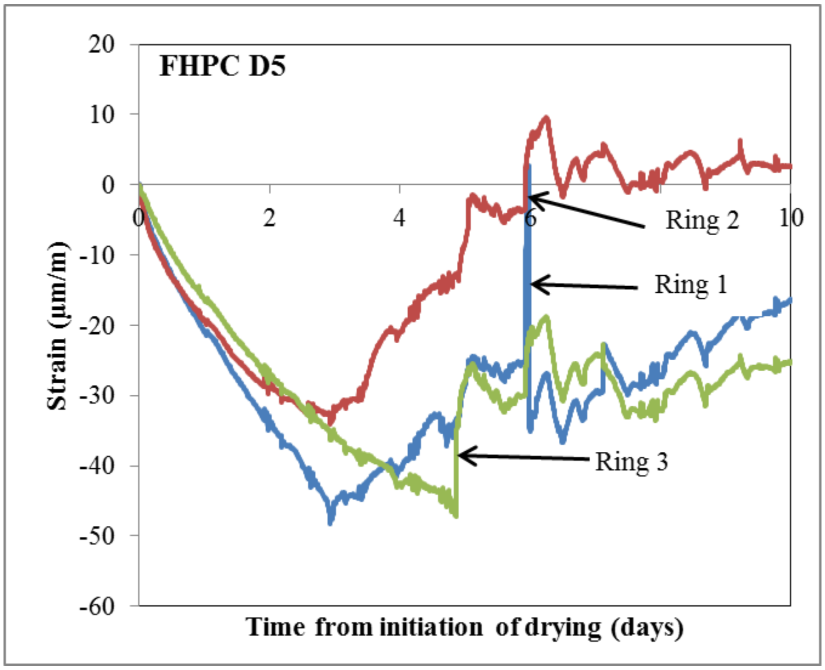


Figure 4.6: Restrained shrinkage strain data for 5lb/yd^3 fiber dosage (FHPC D5)

Similar results were shown in FHPC D7.5 where noise is observed before and after cracking.

Figure 4.7 below shows the restrained shrinkage results for FHPC D7.5.

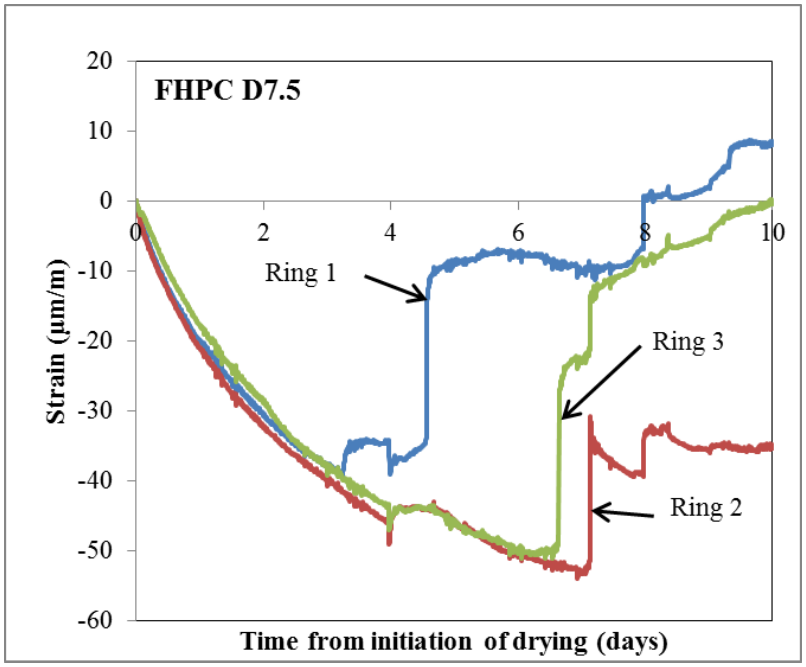


Figure 4.7: Restrained shrinkage strain data for 7.5lb/yd^3 fiber dosage (FHPC D7.5)

The noise observed in FHPC D7.5 was not as pronounced as the noise in FHPC D5 and FHPC D10 (see Figure 4.8 below).

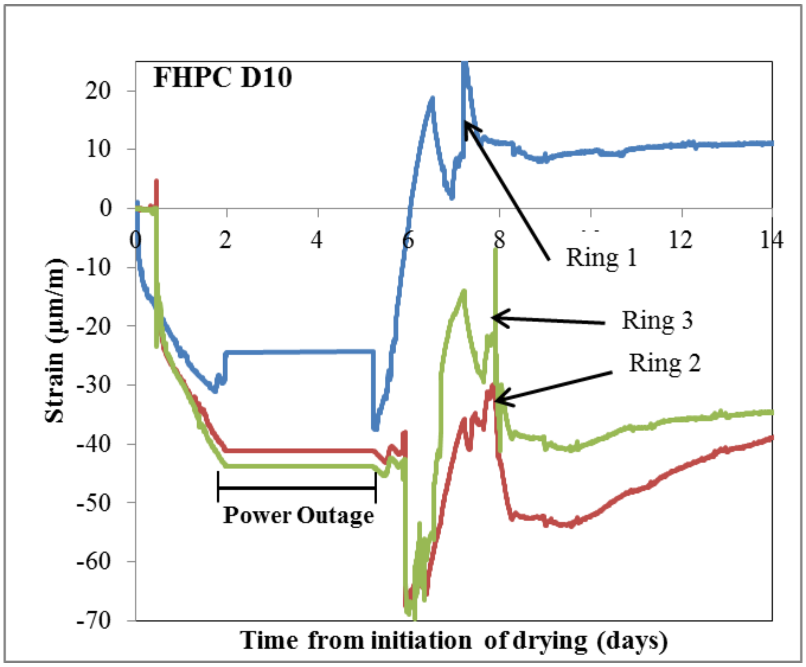


Figure 4.8: Restrained shrinkage strain data for 10lb/^{yd3} fiber dosage (FHPC D10)

Also, in FHPC D10 some data was lost due to power failure. The rings did not crack by visual inspection during the power outage therefore the test was continued. Upon cracking FHPC D10 showed the most significant restraint to cracking. This was shown by the decrease in strain then followed by the sharp jump that indicated cracking. In CHPC (see Figure 4.9 below), the strain data for Ring 1 and Ring 3 showed no clear indication of cracking. By visual inspection the rings cracked at 8 days. In addition, the stress rate was much lower (see Table 4.3) than all other mixtures. This strain behavior was noticed in SPR 728 in the LS (Spratt limestone) mixture (Fu, 2013). The only link between these CHPC and LS is the coarse aggregate angularity, since the aggregates have distinct mineral properties.

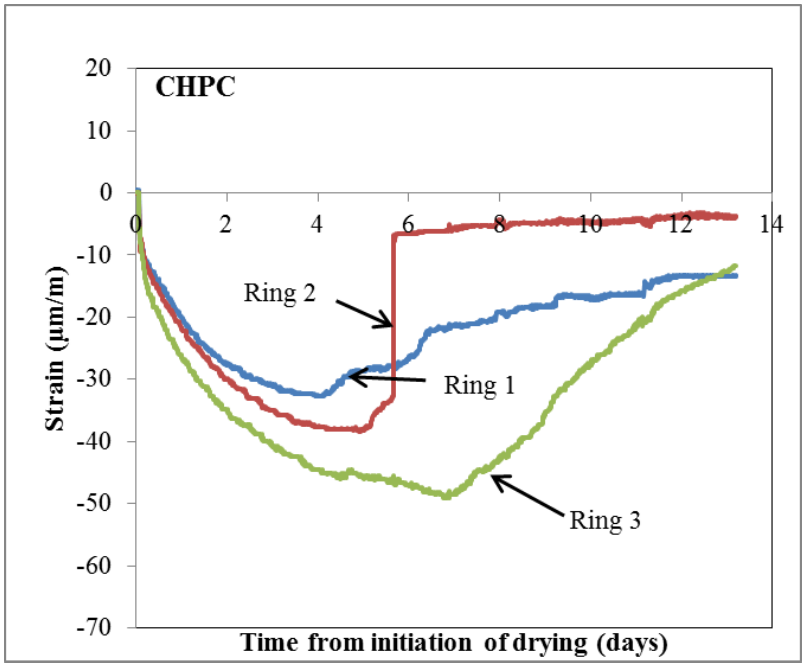


Figure 4.9: Restrained shrinkage strain data for CHPC

Overall, the inclusion of synthetic blended fibers showed improved performance in cracking resistance while being subjected to ASTM 1581. The additional restraint provided by the synthetic fiber blend prolonged the time-to-cracking of the concrete. There may be a link between coarse aggregate angularity and cracking risk of concrete.

4.2.4 CRACK MONITORING

After initial exposure to drying all ring specimens were monitored daily for signs of cracking. After the rings had completely cracked (vertical crack from top to bottom), the cracks widths were measured. The time-to-cracking was shown in the strain data was consistent with visual inspection. Shown below in Figures 4.7-4.9 are the crack widths of all fiber mixtures and the HPC control mixture.

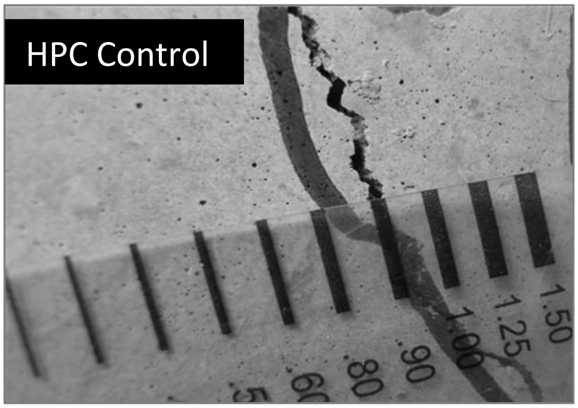


Figure 4.10: Crack width- 0.035in

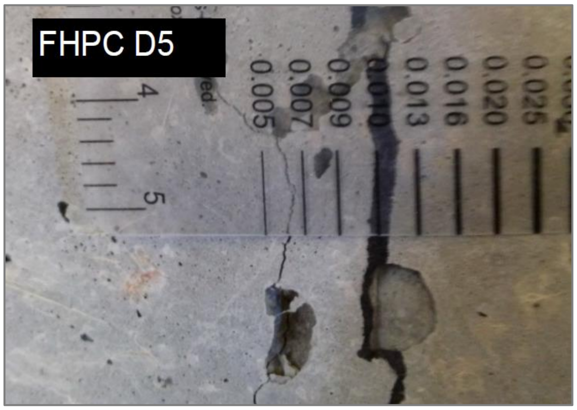


Figure 4.11: Crack width- 0.005in-0.007in

Figure 4.13: Crack width- 0.008in

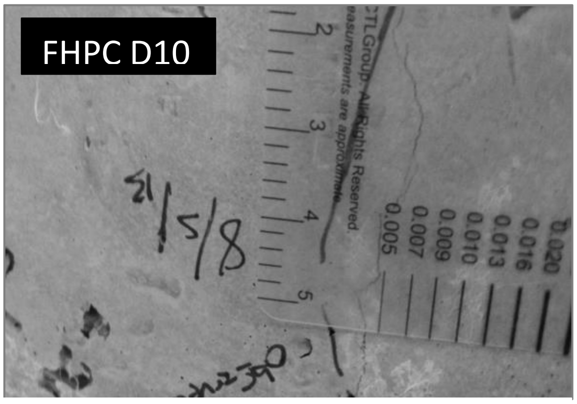


Figure 4.12: Crack width- 0.005in

The crack widths were notably reduced when compared to the HPC control mixture. On average mixtures with fibers showed a crack width of 0.006in when compared to the 0.035in from the HPC control. This suggests that the use of blended synthetic fibers controls cracking and minimizes the chances of future durability concerns.

4.3 Freeze/Thaw ASTM C666

Freeze thaw samples were moist cured for 28 days before being introduced to freezing and thawing conditions. The relative dynamic modulus of elasticity (RDME) was recorded every 36 cycles and the test was terminated at 300 cycles. Only FHPC D7.5 and FHPCD10 were tested for freeze/thaw resistance due to their higher time-to-cracking in the restrained ring test. Both mixtures were air entrained with at least 6.0% air. To pass ASTM C666 the relative dynamic modulus must be above 60% and the specimen must show not show severe signs of degradation over the 300 cycles. RDME results are shown below in Figure 4.14.

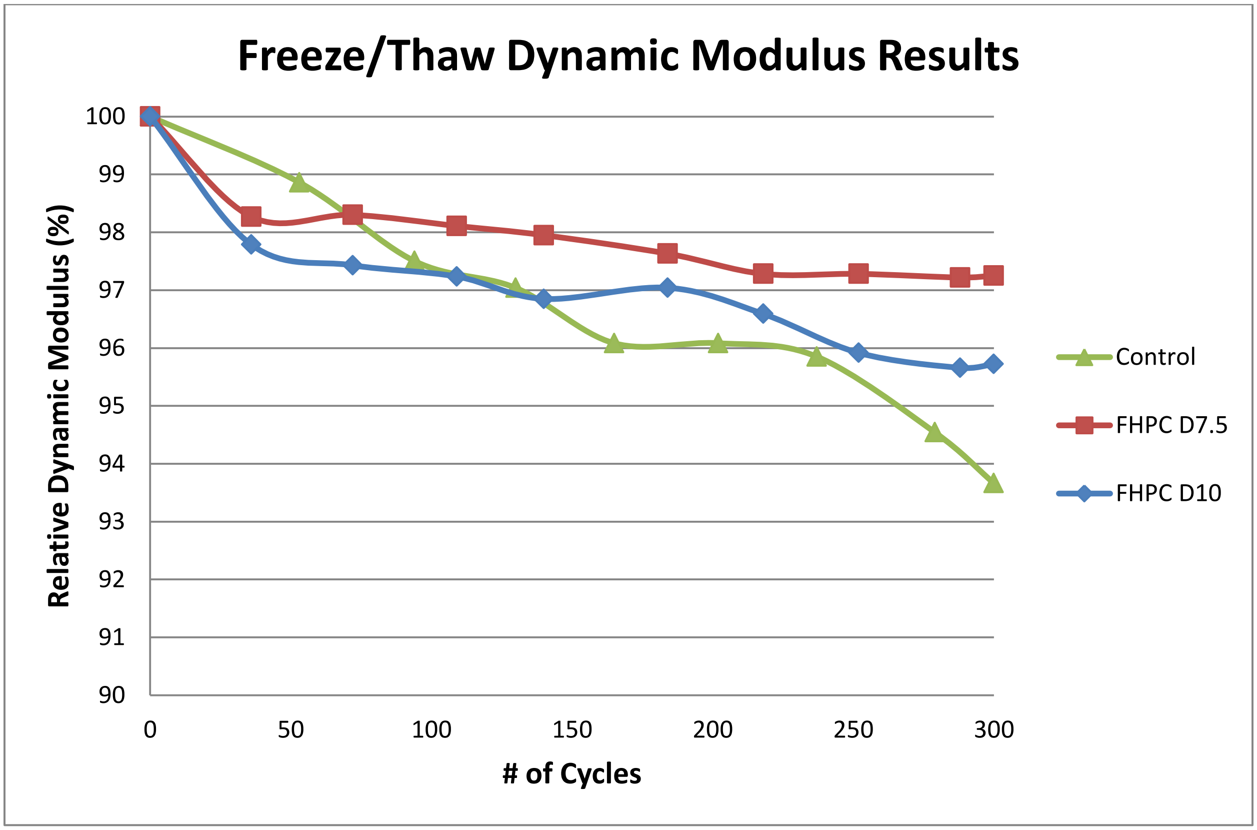


Figure 4.14: Relative Dynamic Modulus of Elasticity Results

The mixtures with fibers had a higher RDME, which suggests that the fibers may increase freeze/thaw performance. In addition to the RDME measurements, the mass was recorded over 300 cycles. Mass change and RDME results are shown in Table 4.4 below.

Table 4.4: Mass Loss and RDME after 300 Cycles

Mixture ID	Mass change (%)	RDME
Control	-0.80	90%
FHPC D7.5	-0.15	97%
FHPC D10	-0.19	96%

The control lost roughly 5 times more mass when compared to FHPC D7.5 and about 4 times more mass when compared to FHPC D10.. However, scaling was observed on all specimens. It was observed that that FHPC D10 had a higher level of scaling than FHPC D7.5. In FHPC D10 more macro-synthetic fibers were exposed at the surface of the specimens. Once these fibers became exposed the paste around the fiber began to scale. Since FHPC D10 had a higher number of macro-synthetic fibers exposed more deterioration was observed. This effect may also be due to the fiber distribution in each specimen. Figure 4.15 shows the FHPC D7.5 specimens after 300 cycles. The specimen on the top showed little to no deterioration. However, the specimen on the bottom showed more macro-synthetic fibers exposed to the surface and some clumping on the left side of the specimen. The clumping of the fibers increased the severity of deterioration due to freezing and thawing. These specimens were cast from the same mixture.

Figure 4.15: FHPC D7.5 specimens after 300 cycles

The clumping effect was also noticed in FHPC D10 where a significant amount of paste and small aggregates were scaled. Figure 4.16 below shows a FHPC D10 specimen after 300 cycles. The area with the highest severity of deterioration is at the right of the specimen where clumping of the fibers is observed.

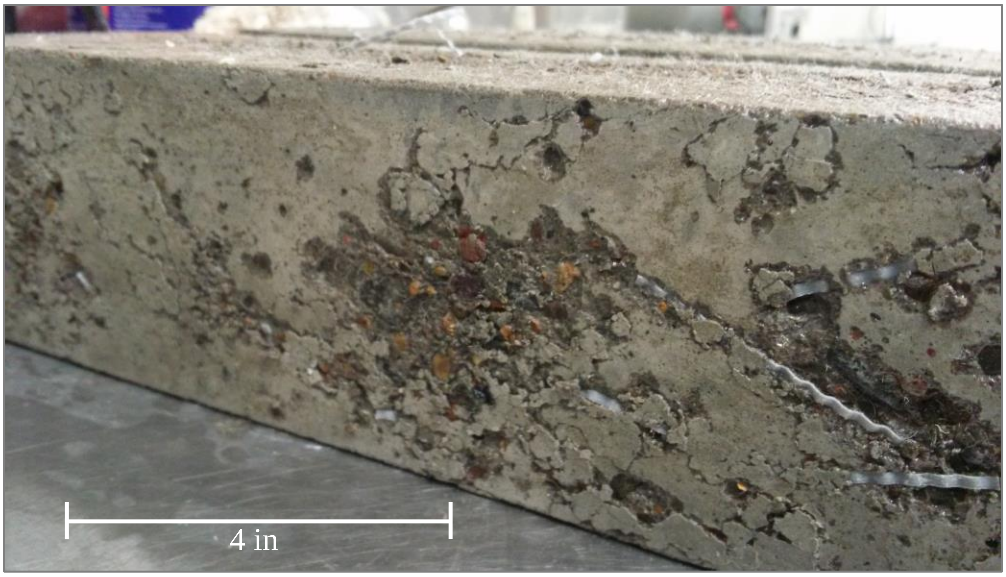


Figure 4.16: FHPC D10 specimen after 300 cycles

Although the fibers may lead to increased scaling during freezing and thawing there was no significant cracking observed and further the RDME was maintained at a higher percentage than the control. The damage shown in figures Figure 4.15 and Figure 4.16 are only on the surfaces of the specimens. The 7.5lb/yd^3 fiber dosage rate showed superior freeze/thaw protection in both visual degradation and RDME.

Similar RDME results were observed by Richardson et al., where the use of micro-synthetic polypropylene fibers provides superior freeze/thaw protection than plain concrete (Richadson et al., 2012). However, it should be noted that Richardson et. al. studied a mixture with low frost resistance (w/cm=0.80), since generally concrete mixtures with a w/cm ratio less than 0.40 do not experience significant durability concerns under freezing/thawing conditions (Jacobsen et al., 1996). The theory behind these findings is that the inclusion of polypropylene reduces water absorption and increases the air void system, and thus increases freeze thaw resistance (Richardson et al., 2012).

4.4 RCPT ASTM C1202

Samples cast for rapid chloride permeability testing were wet cured for 56 days prior to testing. In order to meet the “very low” chloride ion penetrability, according to ASTM C1202, the total charge passed must be below 1000 coulombs. Shown below in Table 4.5 is the total charge passed over the 6-hour duration of the RCPT.

Table 4.5: Total charge passed (RCPT)

Mixture ID	Total Charge Passed

	(Coulombs)
Control	860
FHPC D7.5	560
FHPC D10	693

Although, all samples are within the “very low” category according to ASTM C1202 both fiber dosages reduced the total charge passed. In recent studies, Nayaran found that there was a marginal improvement in total charge passed when using polypropylene fibers (2013). To further investigate the effect of fibers on ion penetrability it is recommended to use a control mixture with higher permeability. A mixture with a higher w/cm ratio and no added SCM’s may be appropriate.

5.0 Conclusions and Recommendations

5.1 Conclusions

In this project the use of blended synthetic fibers for reducing the risk of cracking in high performance concrete was investigated. The impact of shrinkage resulting from modifications to the paste portion of the high performance concrete was also investigated. Standard durability tests, ASTM C666 and ASTM C1202 were also done to determine the impact that the inclusion of fibers had on the freeze-thaw performance and chloride ion penetrability of these mixtures. It was found that:

- The incorporation of fibers at three different dosage rates: 5 lb/yd^3, 7.5 lb/yd^3 and 10 lb/yd^3, had a minimal impact on the 90-day drying shrinkage of high performance concrete specimens, compared to the control. These specimens were wet cured for 14 or 28 days prior to initiation of drying.
- The incorporation of fibers at three different dosage rates: 5 lb/yd^3, 7.5 lb/yd^3 and 10 lb/yd^3, showed a slightly increased amount 90-day drying shrinkage of high performance concrete specimens, compared to the control. These specimens were wet cured for only 3 days prior to initiation of drying.
- The incorporation of fibers into high performance concrete (HPC) increased the time-to-cracking in restrained ring testing over the HPC control and also markedly changed the post-crack behavior of the concrete indicating the fiber’s ability to limit the propagation of cracks once they start forming.

- In restrained ring testing the HPC control mixtures showed average crack widths of 0.035 in. in width. In all mixtures containing fibers, the crack widths were significantly reduced to 0.005-0.008 in.
- The replacement of OPC by 30% slag, rather than 30% fly ash (in the standard HPC control mixture) also showed a reduced amount of shrinkage.
- The incorporation of fibers into HPC was shown to improve the freeze-thaw resistance of the mixtures according to ASTM C666 Procedure A resulting in a higher relative dynamic modulus at the end of 300 cycles compared to the HPC control. There was a slight increase in scaling of the mixtures incorporating fibers, but this appeared to be surficial in nature and did not negatively affect the integrity of the specimens.
- The incorporation of fibers into HPC did not impact the ASTM C 1202 (rapid chloride penetration test) results compared to the control. All mixtures still fell within the "very low" category for chloride ion penetrability.
- Reducing the cement content of the mixtures did not reduce free shrinkage and further reduced strengths slightly below a 4,000 psi minimum threshold.
- One mixture (CHPC) was a high performance concrete mixture where the aggregates were crushed from larger oversize material so that the MSA of ¾" was achieved, but with fractured faces rather than the rounded river gravel typical of use in the Willamette Valley area. Interestingly 2 of the 3 restrained rings in this mixture did not crack during the test duration (28 days after drying initiation) and the stress rate was significantly reduced in this mixture (35 psi/day) compared to the HPC control (54 psi/day).

5.2 Recommendations

Based on the results of this research project the incorporation of fibers into high performance concrete mixtures should reduce the potential for both early and later-age cracking for ODOT bridge decks. The results support that the incorporation of fibers should also help to control crack widths even if cracking does occur in the HPC. Importantly the use of fibers did not impact either freeze-thaw performance or chloride ion penetrability of the mixtures investigated in this study. In fact the incorporation of fibers may further improve the freeze-thaw resistance of HPC. In terms of fiber dosage rates, all those investigated improved concrete properties in terms of cracking resistance. At the higher fiber dosage rate of 10 lb/yd^3 there were marked decreases in concrete workability. These were overcome with increasing dosages of superplasticizer. However, it is not expected that this high of a dosage rate of fibers will provide such significant improvement in performance that the higher dosage rate is justified. Therefore, a dosage rate of 5 lb/yd^3 or 7.5 lb/yd^3 are recommended. These dosage rates may be further modified based on the results of current and/or future HPC decks that incorporate fibers.

5.3 Future Research

The most important recommendation from this research project is to verify the laboratory findings with field experience of HPC incorporating blended fibers. Long-term periodic investigations of the bridge decks will confirm that the use of fibers is 1) reducing or even eliminating cracking in HPC 2) maintaining crack widths that are smaller in width and length compared to HPC without fibers and 3) ensure long-term durability of mixtures incorporating fibers. Further research into the impact of manufactured (e.g. crushed) aggregates compared to rounded river gravels should be undertaken. While only one such mixture was investigated in this study (same siliceous aggregate mineralogy) other research performed under SPR 728 showed that a crushed limestone aggregate also had superior cracking resistance compared to the HPC control with a rounded river gravel. The impact of surface texture on cracking resistance bears further research as a possible method to reduce cracking in high performance concrete.

6.0 References

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Appendix A

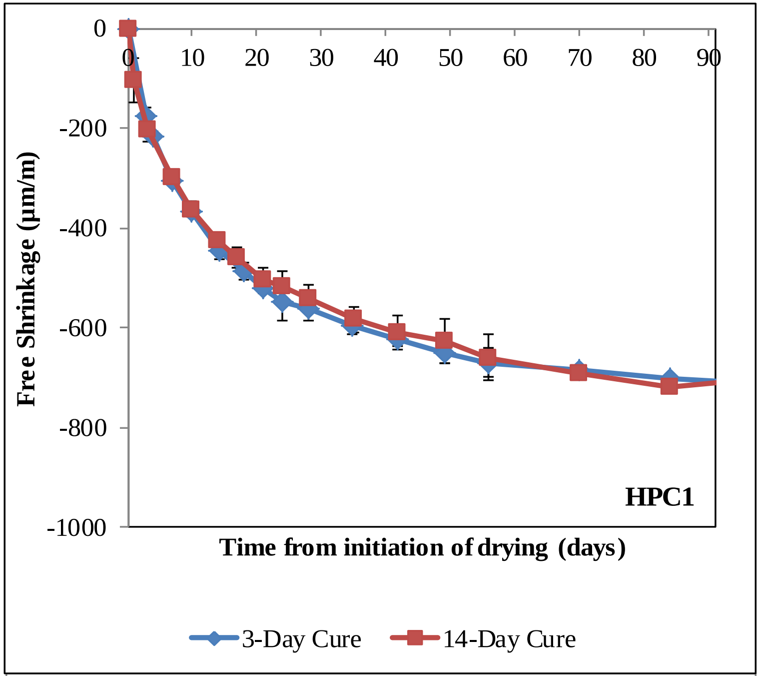
Mix ID:	**HPC1**	Cast date:	4/4/2012	Curing time (days):	**14**
Mix description:	ODOT HPC control mix				

Fresh properties

Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	23.0
Slump (in):	5	Air content (%):	5.0	Unit weight (pcf):	146.5

Hardened properties

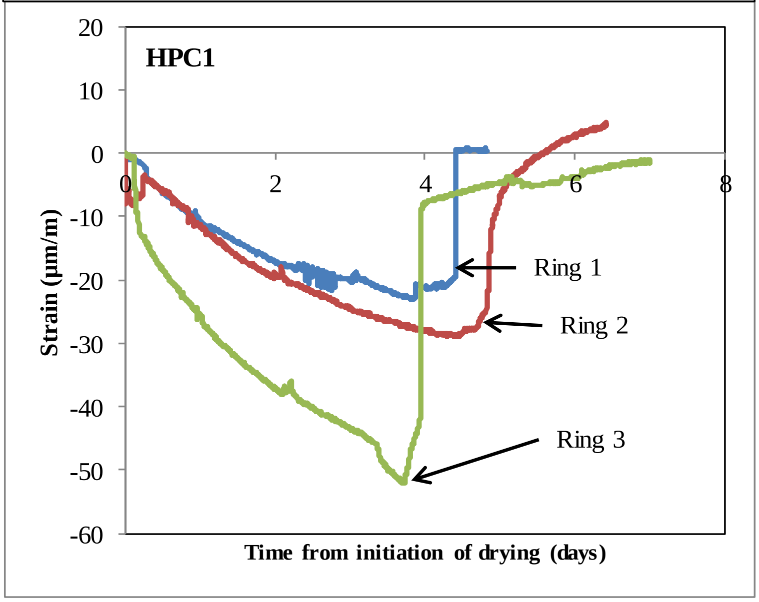
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (psi)	ft (psi)	E (ksi)
5126	588	4679	5787	638	4449



Drying Shrinkage (μm/m)

Approx. Time (Days)	3day Cure	14day Cure
0	0	0
4	-177	-103
7	-307	-203
10	-367	-300
14	-447	-363
21	-487	-503
28	-520	-540
42	-650	-610
56	-670	-660
70	-683	-690
100	-713	-703

**Time is for reference, kept consistant at ±2 days from approximate time



	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring A	4.4	50	**H**
Ring B	4.6	41	
Ring C	3.6	70	
Average	**4.2**	**54**	

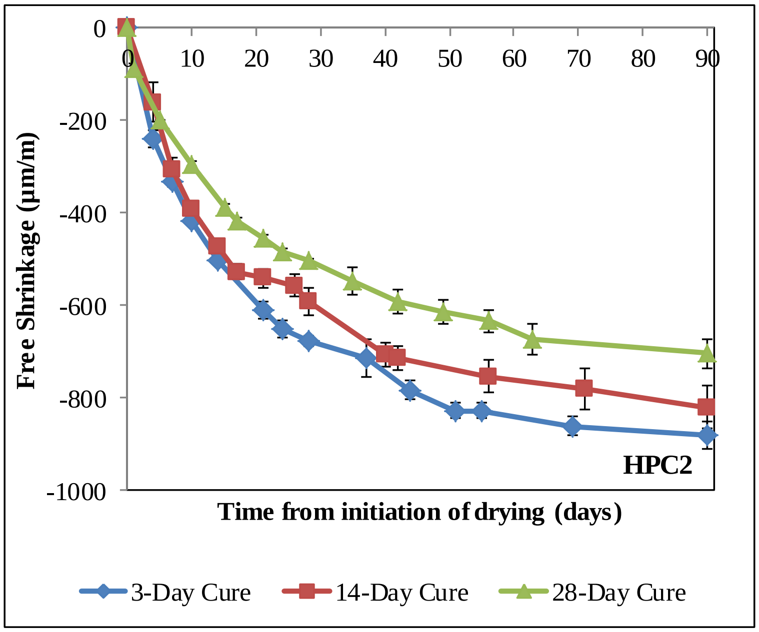
Mix ID:	**HPC2**	Cast date:	7/10/2013	Curing time (days):	**14**
Mix description:	ODOT HPC Control: 30% Slag and 4% Silica Fume replacement				

Fresh properties

Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	20
Slump (in):	3	Air content (%):	6.0	Unit weight (pcf):	143

Hardened properties

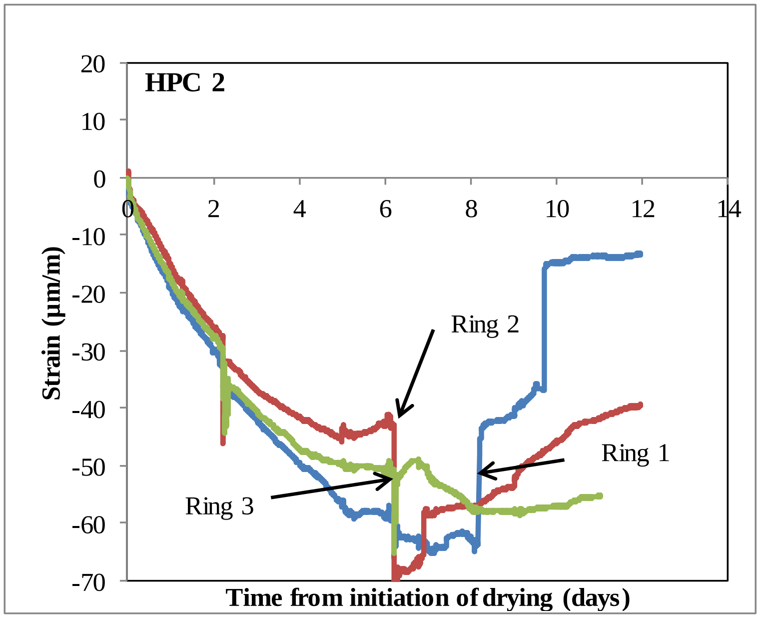
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
4615	485.00	4187.0	-	-	-



Drying Shrinkage (µm/m)

Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-240	-160	-87
7	-333	-307	-200
10	-417	-390	-293
14	-503	-473	-387
21	-610	-540	-453
28	-677	-590	-503
42	-783	-713	-590
56	-827	-753	-633
70	-860	-780	-
90	-880	-820	-703

**Time is for reference, kept consistant at ±2 days from approximate time



	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring 1	8.2	43	**MH**
Ring 2	6.2	48	
Ring 3	6.2	40	
Average	**6.9**	**44**	

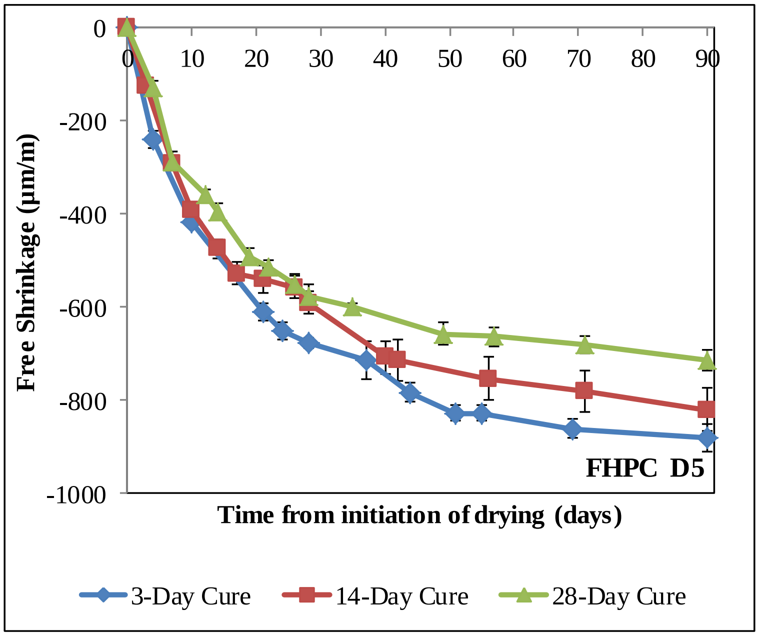
Mix ID:	**FHPC D5**	Cast date:	5/22/2013	Curing time (days):	**14**
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 5lb/yd^3				

Fresh properties

Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	22
Slump (in):	2.5	Air content (%):	6.2	Unit weight (pcf):	143

Hardened properties

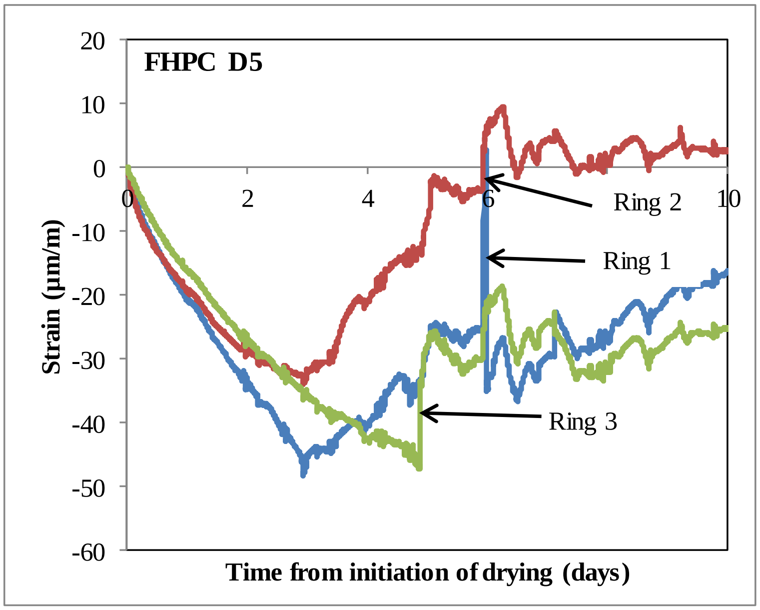
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
3930.0	462.00	3480.0	-	-	-



Drying Shrinkage (µm/m)

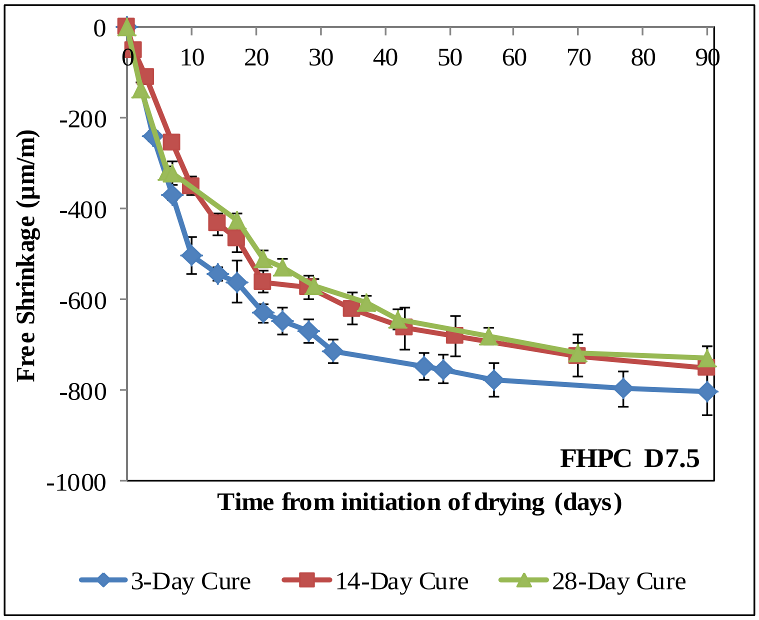
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-240	-123	-130
7	-417	-290	-287
10	-610	-390	-357
14	-650	-473	-393
21	-610	-540	-513
28	-650	-590	-577
42	-677	-713	-
56	-827	-753	-663
70	-860	-780	-680
90	-880	-820	-713

**Time is for reference, kept consistant at ±2 days from approximate time



	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring 1	5.9	64	**H**
Ring 2	5.9	45	
Ring 3	4.9	56	
Average	**5.6**	**55**	

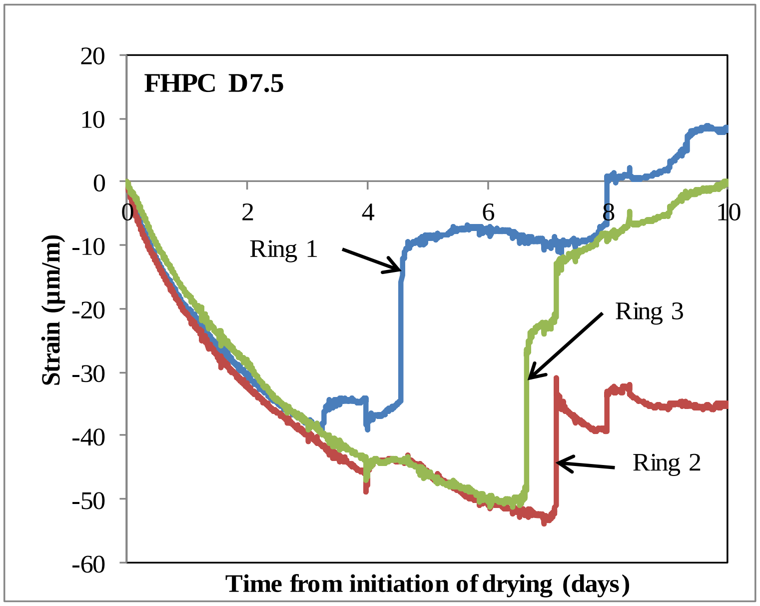
Mix ID:	**FHPC D7.5**	Cast date:	8/28/2012	Curing time (days):	**14**
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 7.5lb/yd^3				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	24
Slump (in):	5.5	Air content (%):	7.0	Unit weight (pcf):	140
Hardened properties					
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
4050.0	436.00	3910.0	5010.0	536.00	4110.0



Drying Shrinkage (µm/m)

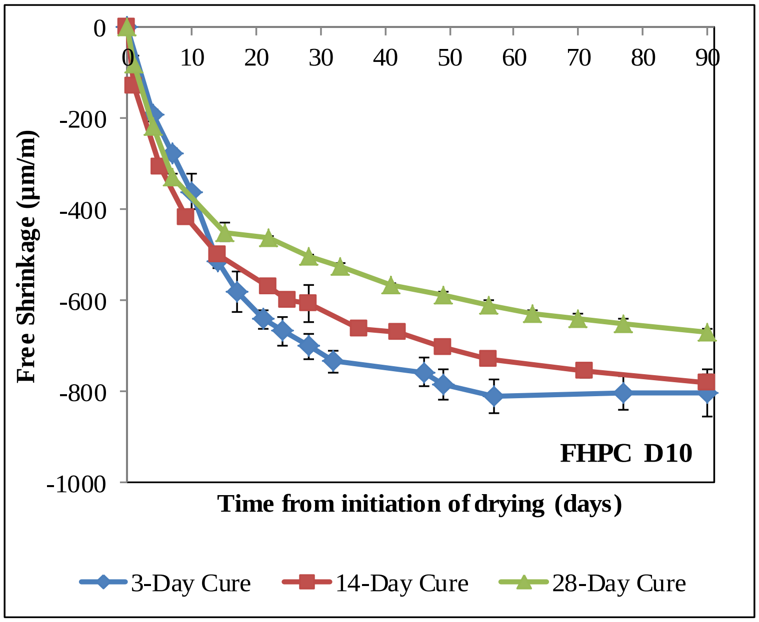
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-240	-50	-137
7	-370	-110	-317
10	-503	-253	-320
14	-543	-350	-393
21	-630	-433	-510
28	-670	-573	-573
42	-747	-663	-663
56	-777	-680	-680
70	-797	-723	-717
90	-803	-750	-727

**Time is for reference, kept consistant at ±2 days from approximate time



	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring 1	4.6	53	**H**
Ring 2	7.1	51	
Ring 3	6.6	53	
Average	**6.1**	**52**	

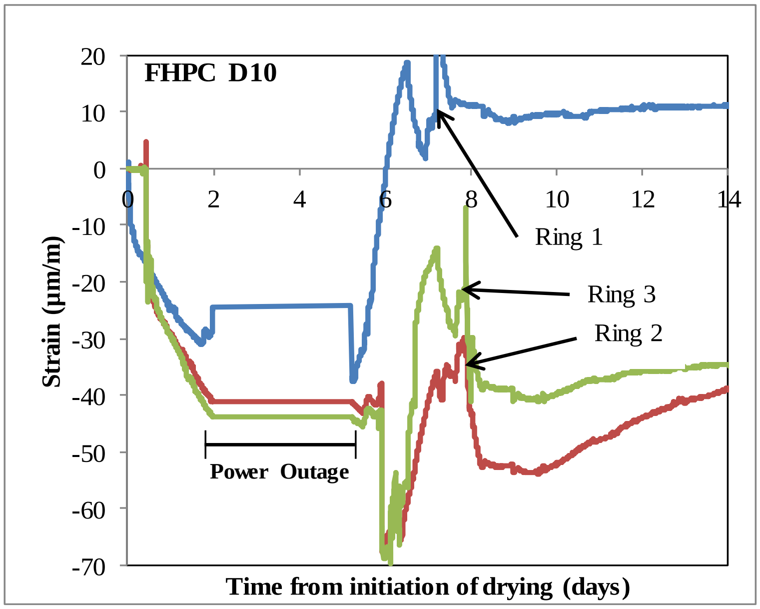
Mix ID:	**FHPC D10**	Cast date:	7/10/2013	Curing time (days):	**14**
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 10lb/yd^3				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	20
Slump (in):	3	Air content (%):	6.0	Unit weight (pcf):	143
Hardened properties					
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
4090.0	520.00	3910.0	5180.0	511.00	4230.0



Drying Shrinkage (µm/m)

Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-190	-130	-217
7	-277	-307	-330
10	-360	-417	-
14	-513	-500	-450
21	-640	-570	-463
28	-700	-607	-503
42	-757	-670	-567
56	-810	-727	-610
70	-803	-753	-640
90	-803	-780	-670

**Time is for reference, kept consistant at ±2 days from approximate time



	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring 1	7.2	49	**MH**
Ring 2	8.0	54	
Ring 3	7.9	56	
Average	**7.7**	**53**	

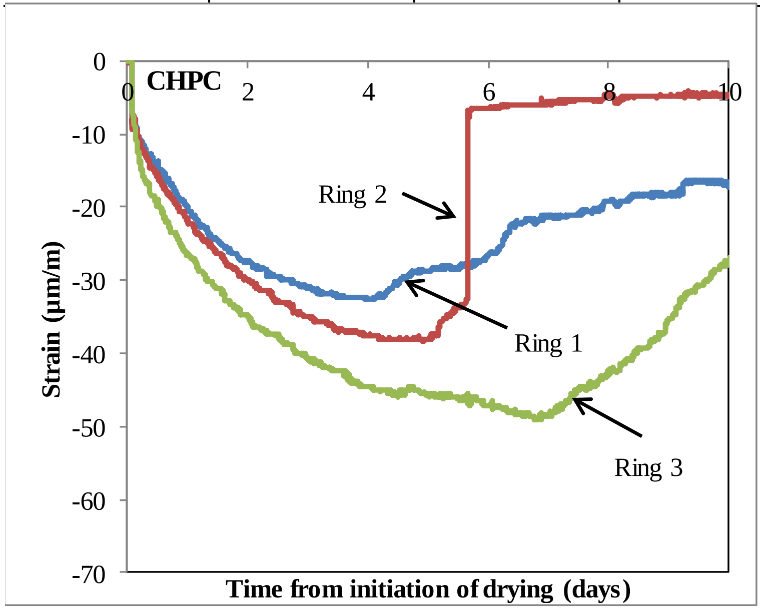
Mix ID:	**CHPC**	Cast date:	12/19/2013	Curing time (days):	**14**
Mix description:	ODOT HPC w/ Crushed Coarse 3/4" MSA				

Fresh properties

Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	22
Slump (in):	3.3	Air content (%):	7.5	Unit weight (pcf):	139

Hardened properties

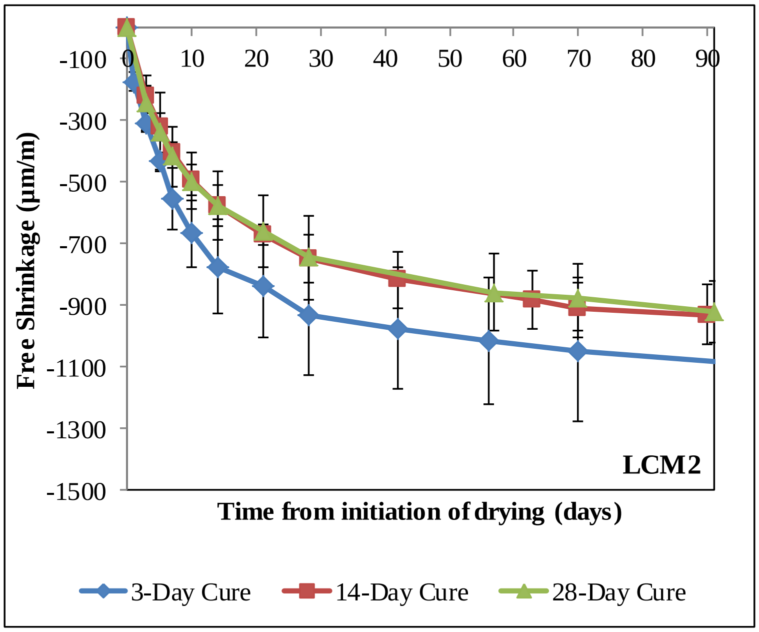
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
2979	392	3590	3090	392	3470



	ToC (days)	Stress Rate (psi/day)	Crack Risk Rating
Ring 1	-	37	**MH**
Ring 2	5.7	32	
Ring 3	-	38	
Average	**5.7**	**36**	

** Ring 1 and Ring 2 Cracked at 8 days by visual inspection

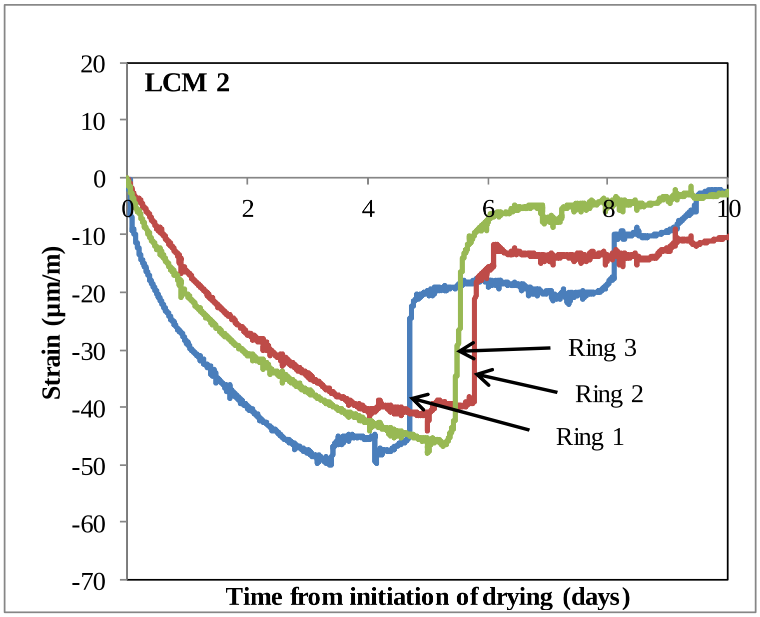
Mix ID:	**LCM2**	Cast date:	10/5/2012	Curing time (days):	**14**
Mix description:	Low Cement Content (550lb/yd^3) HPC Mix				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	24
Slump (in):	3	Air content (%):	8.0	Unit weight (pcf):	135
Hardened properties					
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
2979	392	3590	3090	392	3470



Drying Shrinkage (μm/m)

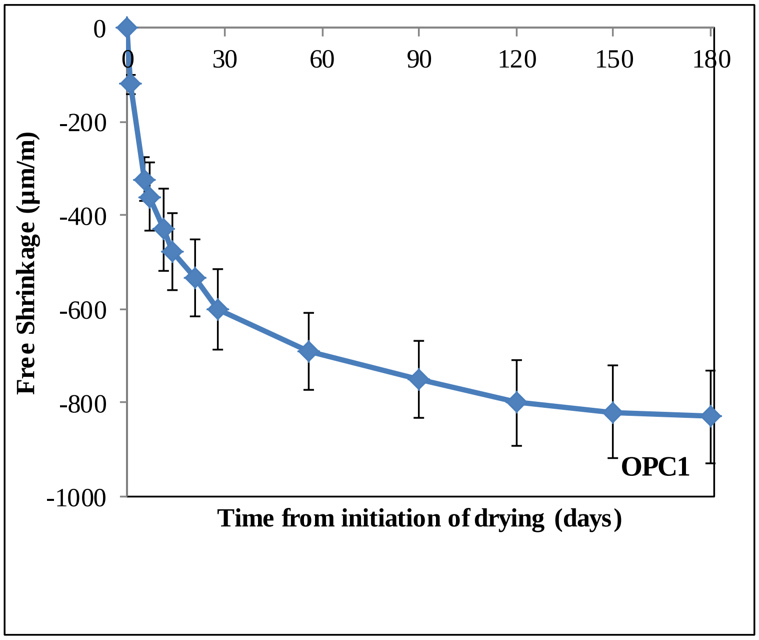
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-240	-220	-240
7	-333	-320	-337
10	-417	-403	-417
14	-503	-493	-497
21	-610	-573	-577
28	-650	-670	-660
42	-677	-750	-743
56	-713	-	-857
70	-783	-907	-873
90	-	-930	-920

**Time is for reference, kept consistant at ±2 days from approximate time



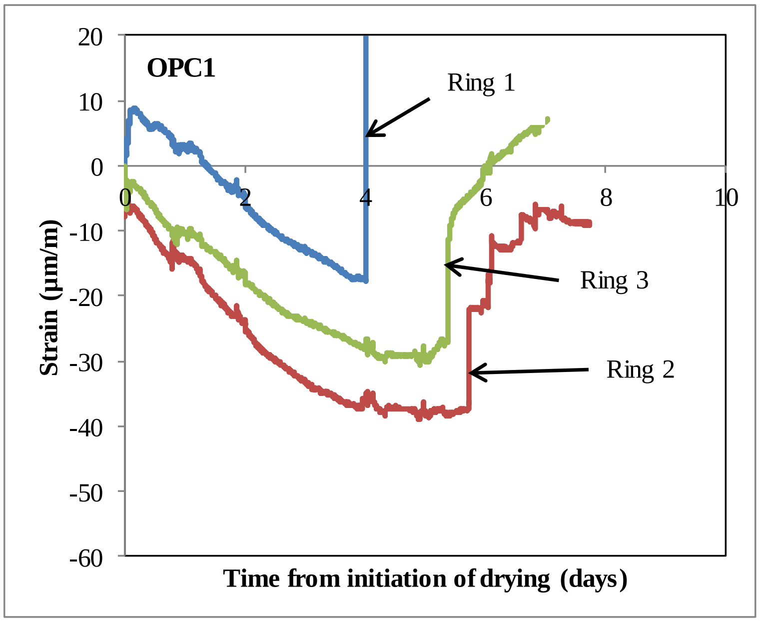
	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring 1	4.7	87	**H**
Ring 2	5.5	78	
Ring 3	5.8	64	
Average	**5.3**	**76**	

Mix ID:	**OPC1**	Cast date:	7/18/2012	Curing time (days):	**14**
Mix description:	OPC w/ no SCM's				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	23.8
Slump (in):	8	Air content (%):	3.0	Unit weight (pcf):	151.1
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (psi)	ft (psi)	E (ksi)
6480	533	5260	6620	622	5400



Approx. Time (Days)	14 day Shrinkage (µm/m)
0	0
1	-120
5	-323
7	-360
11	-430
14	-477
21	-533
28	-600
56	-690
90	-750

**Time is for reference, kept consistant at ±2 days from approximate time



	ToC (days)	**Stress Rate (psi/day)**	Crack Risk Rating
Ring 1	2.7	40	**MH**
Ring 2	5.7	56	
Ring 3	5.4	46	
Average	**4.6**	**47**	

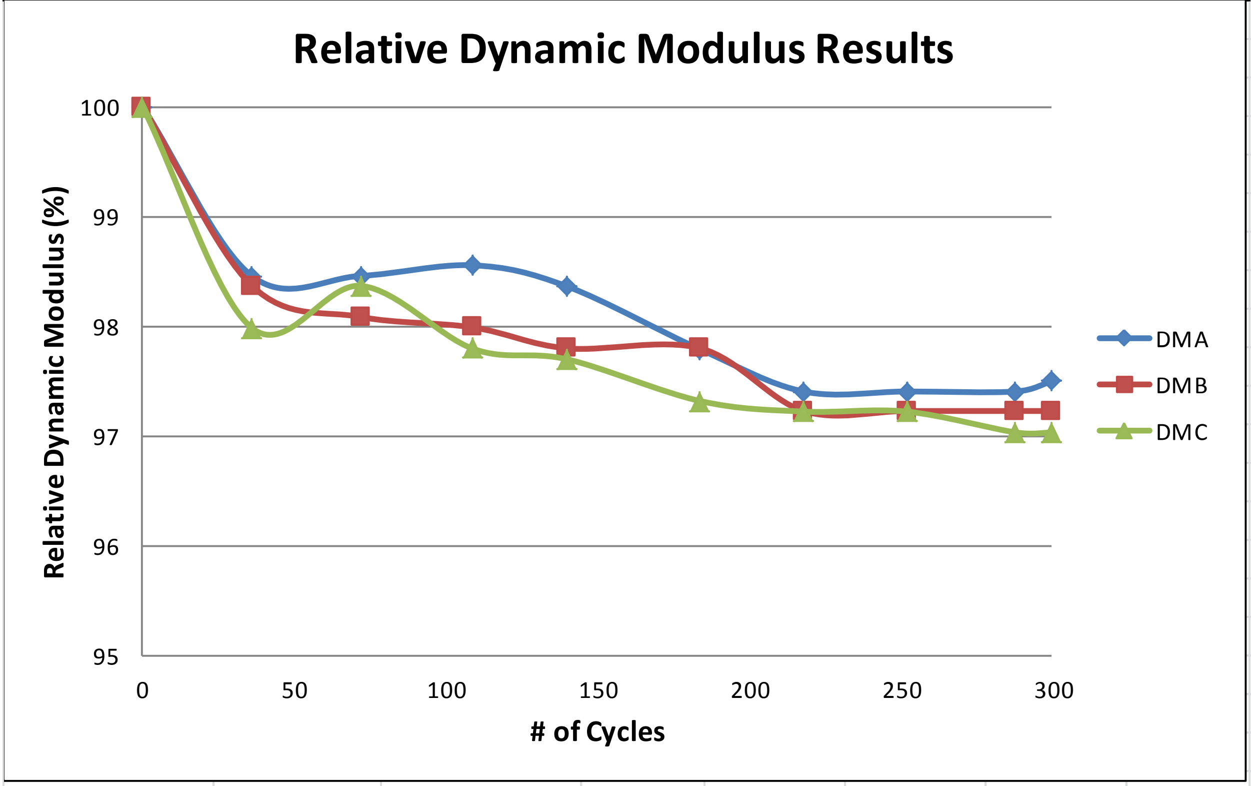
Mix ID:	**FHPC D7.5**	Cast date:	7/18/2012	Curing time (days):	**14**
Mix description:	Synthetic Blended Fiber Freeze/Thaw Mix: Dosage Rate 7.5lb/yd^3				

Fresh properties

Batch size(cu ft):	2.5	w/cm:	0.37	Temperature (°C):	24.0
Slump (in):	2.5	Air content (%):	6.0	Unit weight (pcf):	140.0

Dynamic Modulus (DM)

# of Cycles	DMA	DMB	DMC	DMA (%)	DMB (%)	DMC (%)	Avg (%)
0	2065	2075	2071	100.0	100.0	100.0	100.0
36	2049	2058	2050	98.5	98.4	98.0	98.3
72	2049	2055	2054	98.5	98.1	98.4	98.3
109	2050	2054	2048	98.6	98.0	97.8	98.1
140	2048	2052	2047	98.4	97.8	97.7	98.0
184	2042	2052	2043	97.8	97.8	97.3	97.6
218	2038	2046	2042	97.4	97.2	97.2	97.3
252	2038	2046	2042	97.4	97.2	97.2	97.3
288	2038	2046	2040	97.4	97.2	97.0	97.2
300	2039	2046	2040	97.5	97.2	97.0	97.3



Mix ID:	**FHPC D10**	Cast date:	7/18/2012	Curing time (days):		**14**	
Mix description:	Synthetic Blended Fiber Freeze/Thaw Mix: Dosage Rate 10lb/yd^3						
Fresh properties							
Batch size(cu ft):	2.5	w/cm:	0.37	Temperature (°C):		26.0	
Slump (in):	2.5	Air content (%):	6.0	Unit weight (pcf):		140.0	
Dynamic Modulus (DM)							
# of Cycles	**DM-A**	**DM-B**	**DM-C**	**DM-A (%)**	**DM-B (%)**	**DM-C (%)**	**Avg (%)**
0	2032	2028	2048	100.0	100.0	100.0	100.0
36	2015	1997	2028	98.3	97.0	98.1	97.8
72	2010	1996	2023	97.8	96.9	97.6	97.4
109	2008	1995	2020	97.7	96.8	97.3	97.2
140	2006	1990	2015	97.5	96.3	96.8	96.8
184	2004	1990	2023	97.3	96.3	97.6	97.0
218	1994	1989	2020	96.3	96.2	97.3	96.6
252	1991	1975	2016	96.0	94.8	96.9	95.9
288	1989	1970	2015	95.8	94.4	96.8	95.7
300	1988	1970	2018	95.7	94.4	97.1	95.7