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

Final Report

SRS 500-620

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16. Abstract

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.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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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 damage to the bridge structure may 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 (length and 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.

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 performance of concrete structures (bridge-decks, slabs, pavements 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 *(Kovler et al. 1992)*. Fiber reinforcement made of steel or other artificial fibers has been documented to affected ductility, crack widths and even the fresh properties of cement-based materials *(Saje et al., 2011).* In addition, the geometry of the fibers affects the bond between the fibers and the concrete matrix *(Swamy 1994).* 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 *(Banthia and Gupta 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 *(Saje et al. 2006)*. With regards to total shrinkage Kovler et al. stated that there was no significant reduction up to a volumetric content of 0.2% *(Kovler 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 *(Aly et al. 2008).* Myers et al. mentioned that polypropylene fibers exert a very small influence on shrinkage *(Myers et al. 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" *(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. The intent was to identify the cracking resistance under the exposure conditions. Although the testing methods differed, the observations and results from the Florida study informed the current research with respect to cracking resistance of fiber concrete, especially concrete with polypropylene fibers.

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 is currently addressing 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 *(Brooks 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) *(Folliard et al. 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 (Folliard et al. 2006). As the temperature increased, the cracks propagated further into the slab, and the way the cracks 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. In addition, according to Dossey and McCollough, 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 *(Dossey and McCollough 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)*.

In a project by Folliard and co-workers the inclusion of fibers was evaluated both in the laboratory and in the field to assess spalling mitigation specifically. Two steel fibers (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" *(Folliard et* *al. 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 DEPARTMENT OF TRANSPORTATION (VDOT)

Dr. Celik Ozyildirim studied high performance fiber-reinforced concrete for the bridge deck application *(Ozyildirim 2005)*. 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 met the minimum charge passed (2500 coulombs for VDOT) 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:

- The fibers provided residual strength, which was directly proportional to the fiber content, and controlled cracking. Fewer and smaller cracks were observed in the FRC even though the FRC had higher shrinkage than the control.

- During the residual strength test, the deflection had to be controlled through the actuator, which affected the residual strength. The residual strength was higher when the rate was controlled through the actuator (possible limitations to this test).

- The incorporation of fibers reduced workability.

- Pumping in a vertically downward direction reduced 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 was similar 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 C150,2012)*, ASTM C618 Class F fly ash *(ASTM C618, 2009)*, and ASTM C989 Ground Granulated Blast-Furnace Slag *(ASTM C989,2014)*. These materials were manufactured by Lafarge North America. An ASTM C1240 silica fume *(ASTM C1240, 2014)*, Rheomac 100 manufactured by BASF was also used. The oxide analyses for the cementitious materials are shown in Table 3.1.

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 *(ASTM C494, 2013)* (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 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, 2004)*, and modulus of elasticity *(ASTM C469, 2014)*. For each mixture, ϕ4 × 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 demolded 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 C1581) *(ASTM C1581 2009)*. 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 *(ASTM C157, 2006)*, 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 C511 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 C1581, 2009 and AASHTO T334, 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 simulate field curing conditions; 3) mechanical properties at 28-day age were tested on match cured cylinders. Figure 3.1 shows the dimensions and components of both the ASTM and AASHTO ring apparatus.

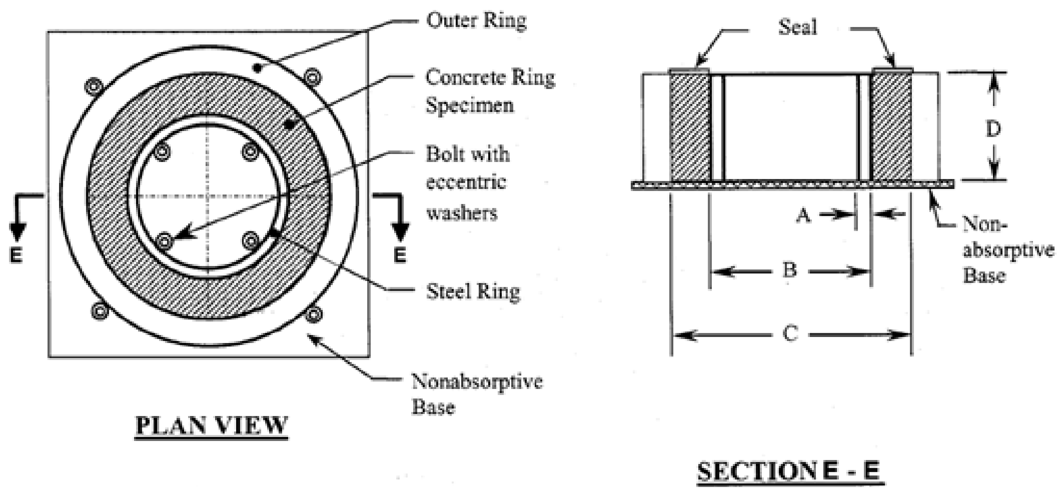

Figure Dimensions	ASTM	AASHTO
A	12.5 ± 0.13 mm	13 ± 0.4 mm
B	330 ± 3 mm	324 ± 5 mm
C	406 ± 3 mm	476 ± 5 mm
D	150 ± 6 mm	152 ± 5 mm

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

A sample of freshly mixed concrete was compacted into three circular molds formed by concentric steel rings. The compressive strain developed in the inner steel ring caused by initial hydration, curing and restrained shrinkage of the specimen under drying was measured from the time of casting. The specimens were moist cured using wet burlap covered with a polyethylene film for at least 24 h at 23.0 ±2.0 °C. The outer rings were 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 specimens was sealed with silicone sealant to allow for drying only in the horizontal direction. The strain gauge readings were recorded every 5 minutes until all 3 concrete rings showed 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.

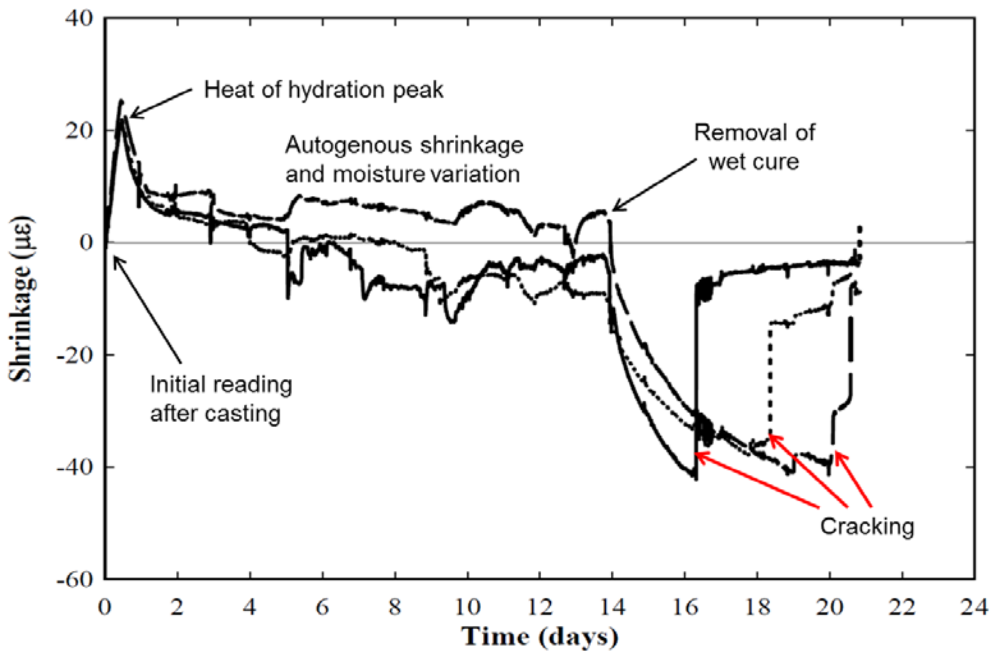

Figure 3.2: A typical averaged strain gauge reading in ring tests (3 replicates) *(Fu and Ideker, 2013)*.

The strain gauge reading was recorded almost immediately (~30 min.) after the specimens were cast and moved into the environmental chamber. It can be seen in Figure 3.2 that the steel ring first registered expansive strain due to the heat released from hydration of the concrete reaching a peak at about 24 hours after casting. After the removal of the outer mold (24hrs from casting), the concrete ring specimens were cured using wet burlap until the end of the desired curing duration. The concrete then cools over the next 24-hour period to the environmental chamber conditions of 23 C +/- 1.5 C. From this point until removal of the wet burlap the concrete most likely experiences some minor autogenous shrinkage. Some fluctuation in the strain gauge reading was also recorded during this period, which may be a result of moisture variation within the sample, or localized stress concentrations due aggregate/mortar arrangement against the steel ring. 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.

Table 3.3: Potential for cracking classification (ASTM 2009)

Net Time-to-Cracking t_{cr} (days)	**Average Stress Rate, S (psi/day)**	**Potential for Cracking**
$0 < t_{cr} \leq 7$	$S \geq 50$	High (H)
$7 < t_{cr} \leq 14$	$25 \leq S < 50$	Moderate-High (MH)
$14 < t_{cr} \leq 28$	$15 \leq S < 25$	Moderate-Low (ML)
$t_{cr} > 28$	$S < 15$	Low (L)

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 (*See et al 2004*). When determining the cracking potential classification, high priority should be given to stress rate at cracking. 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. Shown below is the stress rate equation in accordance with ASTM C1581.

$$\delta_{day} = \frac{G * \alpha}{2 * \sqrt{t}}$$

where:
G = 10.47x10^6 psi
α = slope of strain/sqrt of time graph (10^{-6})
t = average time of cracking

The constant "G" is based on the ring dimensions used in this test method. According to ASTM the stress rate should be calculated at the time-to-cracking or when the test is terminated. However, at the time-to-cracking the stress rate is high due to the sharp jump in the strain, and when the test is terminated the stress rate is low since the rings have already cracked. Therefore, the stress rate was calculated prior to cracking where there was enough strain data to plot the "α" curve and consistently achieve a coefficient of determination (R^2) value above 98%.

3.1.8 Freeze/Thaw Testing

ASTM C666 *(ASTM 666, 2003)* 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 were cast according to ASTM C192 *(ASTM C192, 2014)*, and demolded at an age of 24 +/- ½ hours 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 began. Prior to the initial cycle, the mass and initial fundamental transverse frequency was measured. ASTM *C215 (ASTM C215, 2008)* outlines the procedures for determining the fundamental transverse frequency. Once freeze-thaw cycles began, 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 were 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:

$$P_c = (n_1^2/n^2) \times 100$$

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

The rapid chloride permeability test (RCPT), ASTM C1202, was used to determine the concrete's ability to resist chloride ion penetration *(ASTM C1202, 2012)*. 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 is 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 2 in (50 mm) thick, 4 in (100 mm) diameter piece of concrete during a 6-hour period provides 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 is reduced if the sample is properly cured.

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 was used to evaluate the chloride ion penetrability in qualitative terms.

Table 3.4: Chloride ion penetrability based on charge passed *(ASTM, 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 went 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	234	1810	1110	0
HPC2	419	-	189	25	234	1810	1110	0
FHPC D5	419	189	-	25	234	1810	1110	5
FHPC D7.5	419	189	-	25	234	1810	1110	7.5
FHPC D10	419	189	-	25	234	1810	1110	10
LCM1	363	165	-	22	204	1810	1110	0
LCM2	347	158	-	21	194	1695	1387	0
OPC1	633	-	-	-	234	1810	1110	0
OPC + FA	248	128	-	-	234	1810	1110	0
OPC + SF	361	0	-	25	234	1810	1110	0
CHPC	419	189	-	25	234	1810	1110	0
LS2	419	189	-	25	234	1810	1110	0
F/T D7.5	419	189	-	25	234	1810	1110	7.5
F/T D10	419	189	-	25	234	1810	1110	10

A mixture identification system is described next. HPC represents a high performance concrete mixture. “HPC1” uses Class F fly ash and “HPC2” uses slag. The prefix “F” added to HPC 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 HPC mixture using crushed siliceous river gravel and LS2 is a HPC mixture using crushed limestone. CHPC and LS2 both used siliceous river sand as the fine aggregate. Two low cement mixtures (LCM1 and LCM2) are distinguished by their cement content shown in Table 3.5. In addition to the low cement investigation, mixtures based on ordinary portland cement (OPC), OPC plus fly ash (OPC + FA), and OPC plus silica fume (OPC + SF) were investigated to determine their shrinkage potential. “F/T” are fiber mixtures used for freeze thaw testing and are followed by the fiber dosage rate used. Table 3.6 provides further details on each mixture.

Table 3.6: Mixtures for ASTM C1581 restrained ring tests

Mixture ID	Coarse aggregate type	Fine aggregate type	w/cm	Curing duration (days)	Other descriptions
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
LS2	Limestone	Local	0.37	14	Crushed ¾” MSA
LCM 2	Local	Local	0.37	14	Low Cement Content ¾” MSA
OPC1	Local	Local	0.37	14	¾” MSA

4.0 RESULTS AND DISCUSSION

4.1 FRESH PROPERTIES

Error! Reference source not found. 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
LS2	2.5	5.2	145	19
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	2.0	6.0	140	26

Only mixtures with target air entrainment were tested for restrained and free shrinkage. 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

Mixture ID	28 Day, Wet Cured				28 Day, Match Cured		
	Compressive Strength (psi)	Tensile Strength (psi)	Modulus of Elasticity (ksi)		Compressive Strength (psi)	Tensile Strength (psi)	Modulus of Elasticity (psi)
HPC1	5126 (241)	588 (59)	4679(192)		5787 (513)	638 (4)	4479 (171)
HPC2	4620 (144)	485 (26)	4190 (303)		-	-	-
FHPC1 D5	3930 (236)	462 (0.3)	3480 (72)		-	-	-
FHPC1 D7.5	4050 (102)	536 (13)	3908 (146)		5010 (467)	587 (10)	4107 (66)
FHPC1 D10	4090 (614)	520 (19)	3910 (56)		5180 (265)	511 (22)	4230 (16)
CHPC	3599 (29)	412 (16)	4103 (363)		3920 (81)	345 (5)	3793 (135)
LS2	5710 (126)	529 (42)	4411 (91)		6069 (548)	610 (37)	4745 (85)
LCM 525	3450 (285)	517 (22)	4100 (223)		-	-	-
LCM 550	2980 (59)	392 (23)	3590 (51)		3091 (255)	392 (32)	3470 (78)
OPC 1	6480 (131)	533 (29)	5260 (143)		6624 (579)	622 (51)	5400 (60)

Match cured mechanical properties were notably higher, roughly a 1000 psi increase, than the 28-day cured specimens. This was also noted in a previous study at OSU and was further investigated by Tengfei Fu, PhD and fellow graduate student David Rodriguez *(Rodriguez and Fu 2014)*. Historically, it has been established that longer moist curing durations achieve higher strength. The main goal was to determine if a 14-day wet cure mixture could achieve a higher strength than a 28-day cure mixture at 90 days. Various HPC mixtures were tested using a 0.37 and 0.42 water to cement ratio. Other mixtures included HPC with SRA, HPC using limestone coarse aggregate, and HPC using FLWA. All mixtures used the standard ODOT HPC mix design for bridge decks (as explained in section 3.2). In all mixtures the compressive strength of the 14-day wet cure specimens at 90 days was similar if not slightly lower than the compressive strength of the 28-day wet cure specimens. Moreover, the mixture with coarse limestone showed roughly a 1000psi increase in strength when wet cured for 14 days, rather than 28 days.

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 4000 psi minimum. Additionally, the modulus of elasticity was lowered significantly, which indicated increased ductility. CHPC strengths were lower than expected. The lower strength may have been due to the higher amount of air (7.5%), which was at the higher limit to ensure freeze/thaw protection. Also this mixture may have required 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); therefore, further work may be necessary to ensure that this mixture meets ODOT requirements. The LS2 mixture showed higher compressive strength at 28 days. 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 did not meet ODOT strength requirements.

4.2 FREE SHRINKAGE

4.2.1 Blended Fiber Mixtures

Free drying shrinkage tests of 3, 14, and 28 day curing durations were 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 in Figure 4.1.

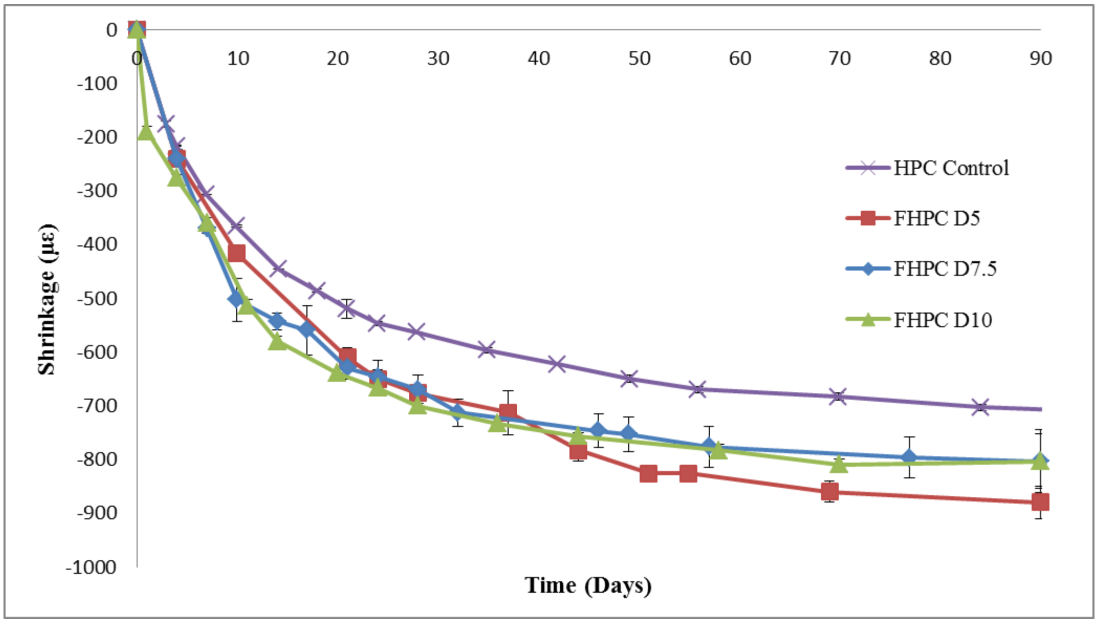

Figure 4.1: 3-day cure free drying shrinkage

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 in Figures 4.2 and 4.3.

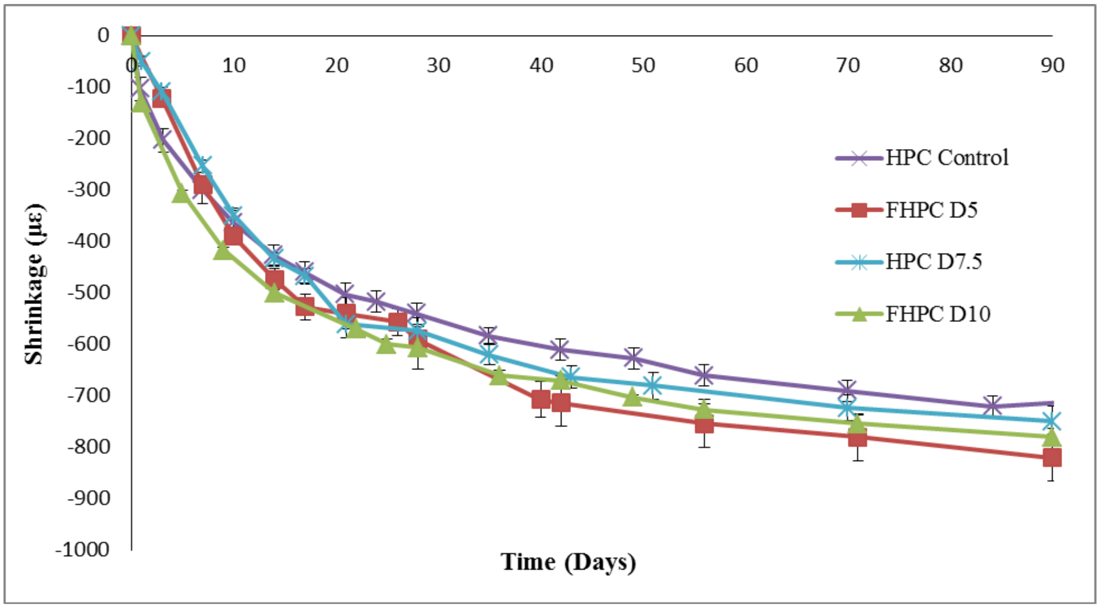

Figure 4.2: 14-day cure free drying shrinkage

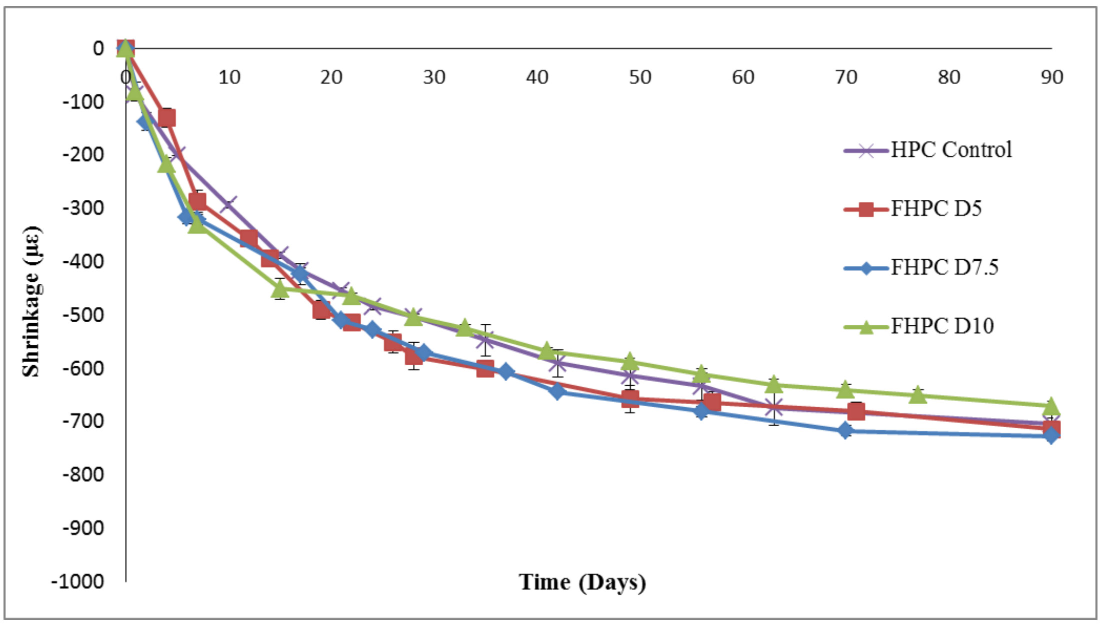

Figure 4.3: 28-day cure free drying shrinkage

The 14 and 28 day curing durations achieved similar drying shrinkage results. 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.

4.2.2 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.

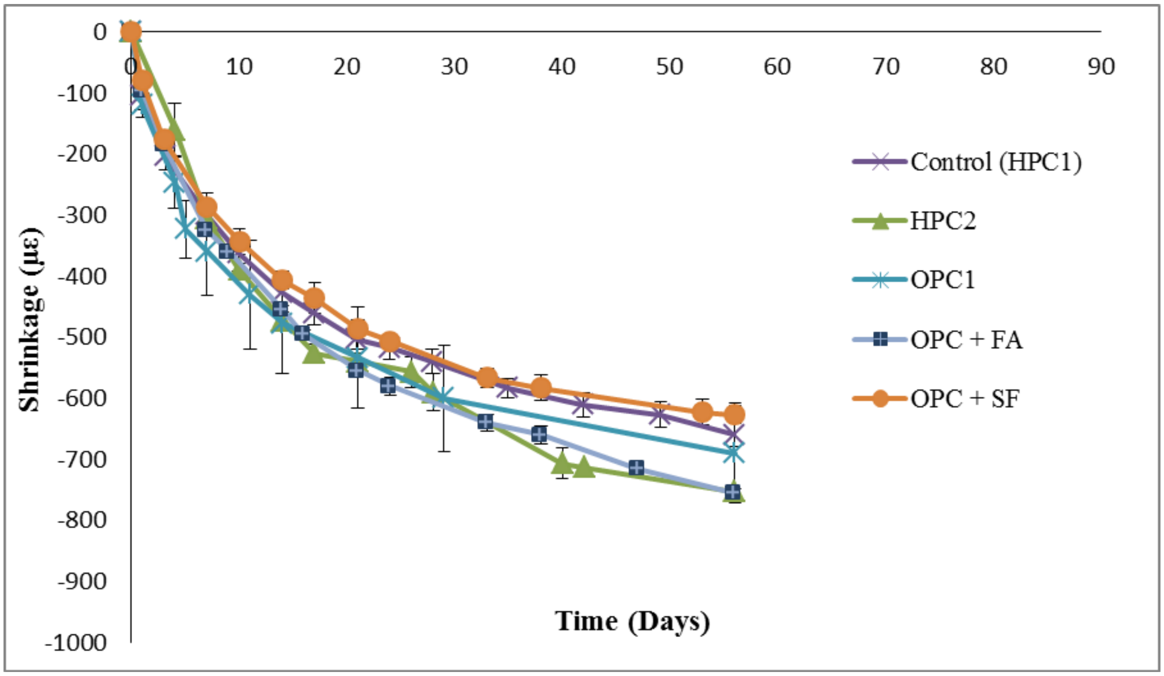

Figure 4.4: 14-day cure free drying shrinkage of mixtures with SCM Modifications

As shown in Figure 4.4 none of the SCM modifications reduced the total shrinkage at 56 days of drying. In addition, mixtures with higher OPC content achieved approximately the same drying shrinkage as the control mixture. However, when using slag at the same replacement level in a high performance mixture, the total drying shrinkage was higher than the original control. 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 *(Subramaniam et al. 2005)*.

Next, the effect of coarse aggregate type and cement content on drying shrinkage was investigated. Previous research at Oregon State University from Fu and Ideker showed that a mixture incorporating limestone (LS) as the coarse aggregate showed low drying shrinkage (457 microstrains at 90 of drying) *(Fu and Ideker 2013)*. The LS mixture used the same ODOT mixture design, siliceous river sand, and angular limestone coarse aggregate. To further investigate the effect of limestone and coarse aggregate angularity on drying shrinkage mixtures using a local crushed limestone and crushed siliceous river gravel (CHPC) were evaluated.

Shown in below in Figure 4.5 are the drying shrinkage results for the mixtures with cement and aggregate modifications.

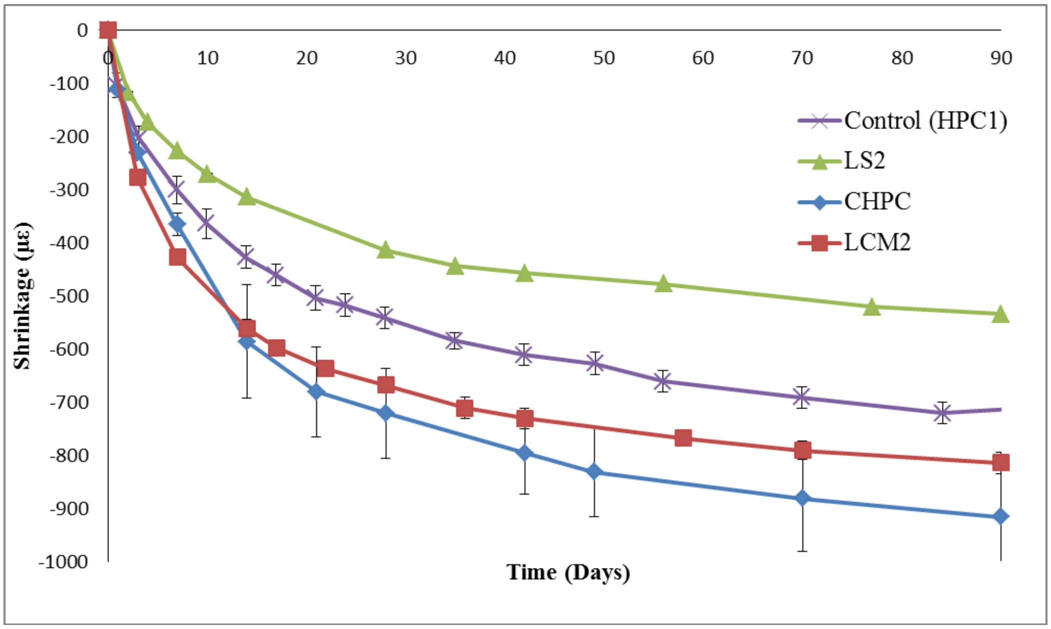

Figure 4.5: 14-day cure free drying shrinkage for mixtures with cement and coarse aggregate modifications

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 *(Darwin 2010)*. In addition, cracking occurs up to 3 times as much in concrete with strength of 6500 psi when compared to concrete with 4500psi strength *(Darwin, 2010)*. The compressive strength was far lower than both the 4500psi suggested by Darwin, and the 4000psi minimum for concrete bridge decks as prescribed by ODOT. However, as shown above lowering the cement content was not successful in reducing the drying shrinkage. 1day cure drying shrinkage results for LCM1 can be found in the appendix (>1000 microstrain at 90days).

Both SCM and cement content modifications had negative results on the drying shrinkage of the ODOT HPC mixture. The limestone mixture (LS2) had a total shrinkage of 533 microstrains at 90 days of drying. The crushed river gravel had adverse effects on drying shrinkage. This suggests that the angularity of the aggregate is not positively correlated with drying shrinkage. These results suggest that the mineralogy of the aggregate had the most significant effect on drying shrinkage, however further work to characterize the aggregate is warranted.

4.3 RESTRAINED SHRINKAGE

4.3.1 Time to Cracking

Table 4.3 provides a summary of the ASTM C1581 ring results, including time-to-cracking and the corresponding stress rate. 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 Length (days)	Time-to-Cracking, (days)				Cracking Potential Classification Based on Time-to-Cracking*	Stress Rate, (psi/day)				Cracking Potential Classification Based on Stress rate*
		1	2	3	Ave.		1	2	3	Ave.	
HPC1	14	4.4	4.6	3.6	4.2	H	50	41	70	54	H
HPC2	14	6.2	6.2	8.2	6.9	H	47	48	40	45	MH
FHPC D5	14	5.9	5.9	4.9	5.6	H	64	45	56	55	H
FHPC D7.5	14	4.6	6.6	7.1	6.1	H	53	51	53	52	H
FHPC D10	14	7.3	7.9	8.0	7.7	MH	49	54	56	53	H
CHPC	14	9	5.7	9	7.9	MH	37	31	37	35	MH
LS2	14	20.5	8.5	23.4	17.5	ML	21	31	18	23	ML
LCM2	14	6.1	3.4	5.2	4.9	H	87	78	64	76	H
OPC1	14	2.7	5.7	5.4	4.6	H	40	56	46	47	MH

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

The first notable result was the difference between HPC1 and HPC2. The average time to cracking of HPC2 was about 3 days longer than HPC1. The main difference between these two mixtures was that HPC1 contained class F fly ash and HPC2 contained slag. The shrinkage investigation discussed in section 4.2.2 showed 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 to cracking in the rings by roughly 1 day when compared to HPC1.

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-to-cracking when applying synthetic blended fibers at a 5lb/yd^3, 7.5lb/yd^3, and 10lb/yd^3 dosage rate respectively (compared to HPC1). However, the use of slag at a 30% replacement had a similar reduction in time-to-cracking compared to concrete with fibers.

The fiber mixtures showed no difference in stress rate when compared to HPC1. The stress rate, as previously mentioned, was calculated prior to cracking. The compressive strain developed during this time is mainly due to drying shrinkage. This suggests that higher strain due to drying shrinkage was developed prior to cracking in the fiber mixtures. The stress rate is a function of the time-to-cracking and the slope of the strain/time graph (see section 3.1.7). Therefore, although the time-to-cracking was increased, no significant reduction in stress rate was observed due to the higher slope of the strain/time graph prior to cracking.

4.3.2 Strain Behavior

One of the most significant observations is the strain behavior in the concrete containing fibers before and after cracking. Typically, it was observed that in concrete with no fibers the strain curves sharply decreased (steep slope) and then a nearly vertical change in strain to near zero was observed at the time of cracking as shown in Figure 4.6. The strain behavior was markedly different when fibers were added, particularly FHPC D5 and FHPC D10, as shown in Figures 4.7 - 4.9. First, instead of an abrupt decrease in strain there was a gradual decrease with a considerable amount of fluctuation. This was likely due to the synthetic fibers, which provided crack propagation resistance, as the compressive strain due to drying overcame the tensile strength of the concrete matrix. In addition, after the specimens started to crack there was a more gradual reduction in stress rather than the sharp stress release observed in mixtures without fibers. This suggests that the fibers continued to provide cracking resistance after the ring had cracked. Another observation was 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.

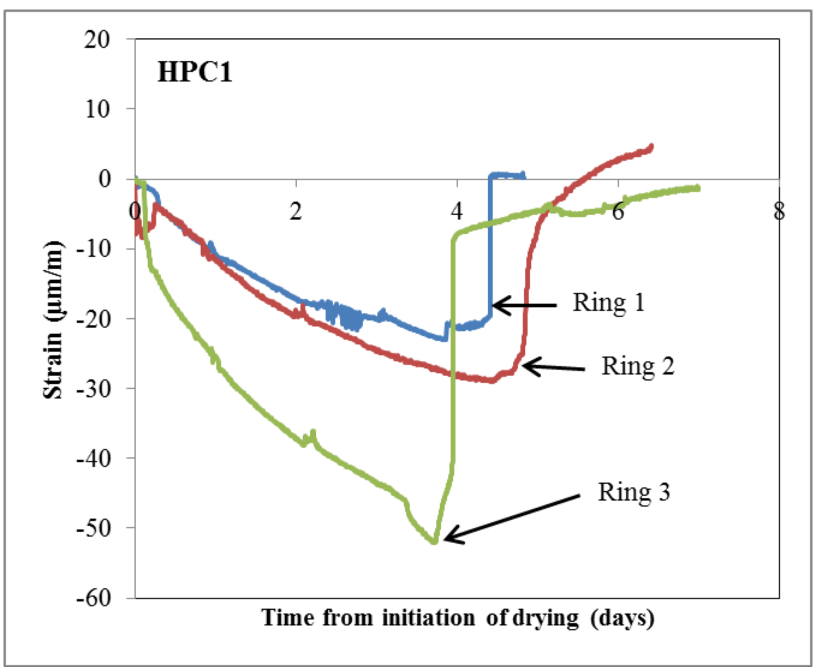

Figure 4.6: Restrained shrinkage strain data for control

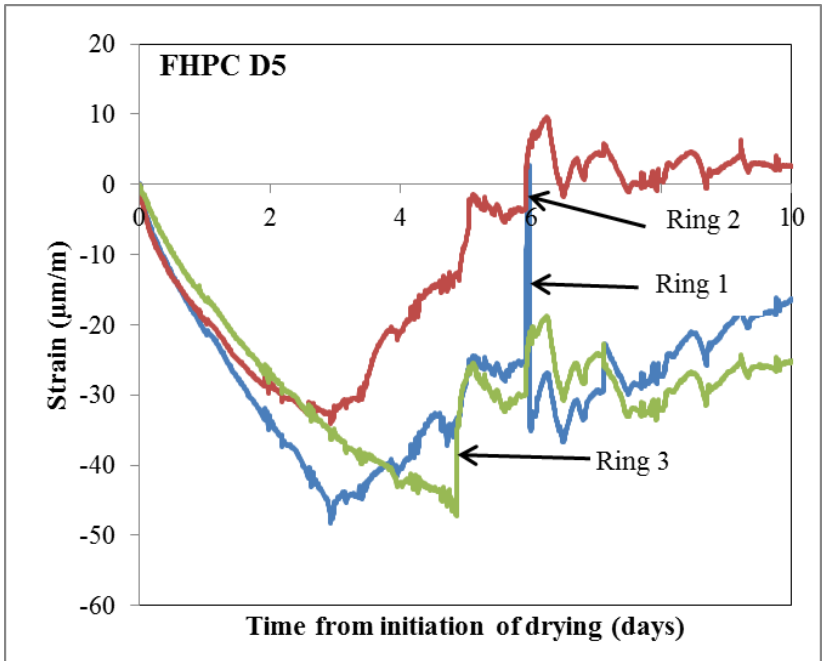

Figure 4.7: Restrained shrinkage strain data for 5lb/yd^3 fiber dosage (FHPC D5)

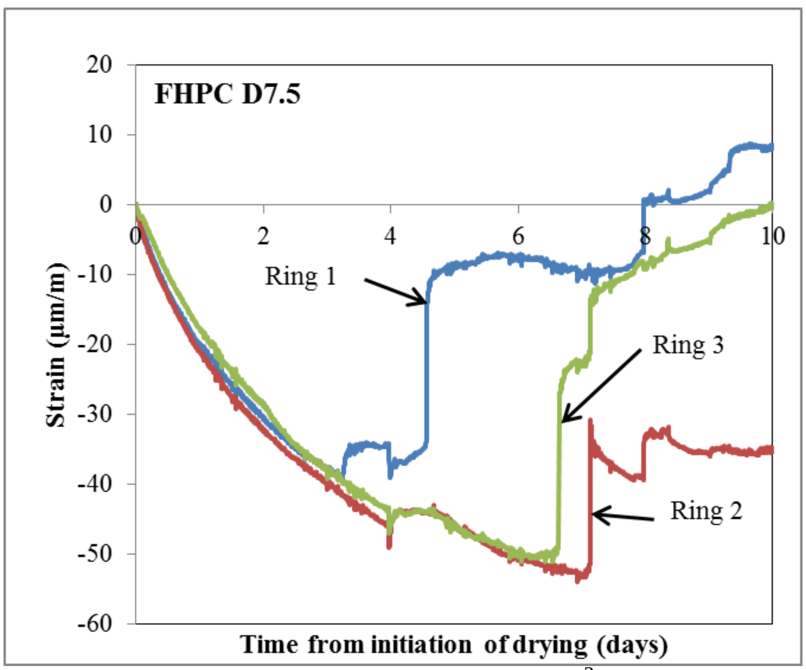

Figure 4.8: Restrained shrinkage strain data for 7.5lb/yd^3 fiber dosage (FHPC D7.5)

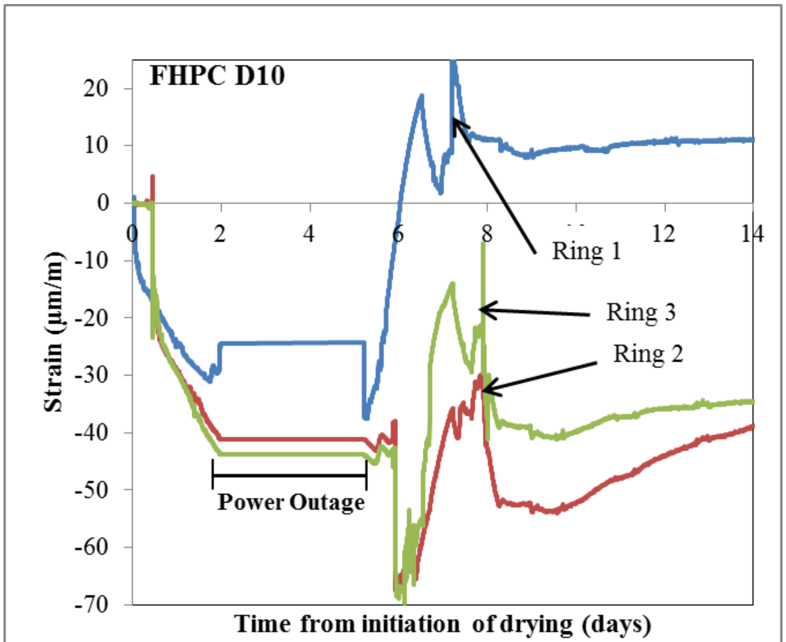

Figure 4.9: Restrained shrinkage strain data for 10lb/yd^3 fiber dosage (FHPC D10)

For FHPC D10 some data were lost due to power failure. Based on visual inspection, no cracking was observed during the power outage; therefore, the test was continued. Upon cracking FHPC D10 showed more restraint to cracking compared to HPC1. The data showed some reduction in stress between 6 and 7.5 days indicating that there was some internal cracking that was restrained by the fibers. At the time of cracking, the sharp decrease in strain was not as pronounced as it was in the HPC1 mixture.

Overall, the inclusion of synthetic blended fibers showed a slight increase in time-to-cracking as well as reduced crack widths (discussed further in Section 4.3.3). However, the stress rate generation was not different between the mixtures incorporating fibers and HPC 1. The additional restraint provided by the synthetic fiber blend prolonged the time-to-cracking of the concrete and also reduced crack widths significantly once cracking initiated.

In CHPC (see Figure 4.10), the strain data for Ring 1 and Ring 3 showed no clear indication of cracking. By visual inspection the rings cracked at 9 days. In addition, the stress rate was much lower (see Table 4.3) than all other mixtures. This strain behavior also was noticed in previous work in the mixtures containing Spratt limestone aggregate (Fu and Ideker 2013). The only similarity between the CHPC and the mixtures with limestone aggregate was the coarse aggregate angularity. Consequently, there may be a link between coarse aggregate angularity and cracking risk of concrete. Shown in Figure 4.10 is the restrained shrinkage data for the limestone mixture LS2. LS2 showed the lowest cracking risk, which was shown in both the time-to-cracking (17.5 days average) and the stress rate (23 psi/day average). Ring 2 cracked earlier than Rings 1 and 3 (8.7 days of drying); regardless, the overall potential for cracking remained in the ML category.

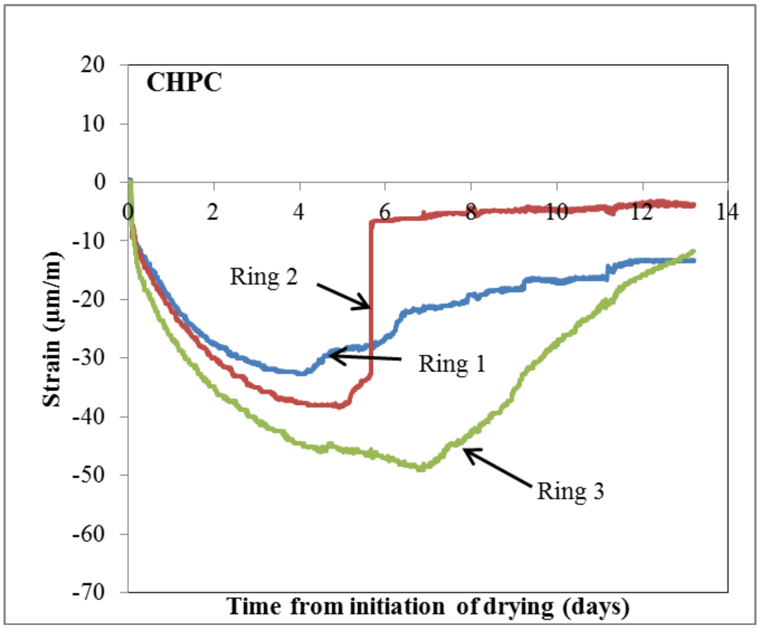

Figure 4.10: Restrained shrinkage strain data for CHPC

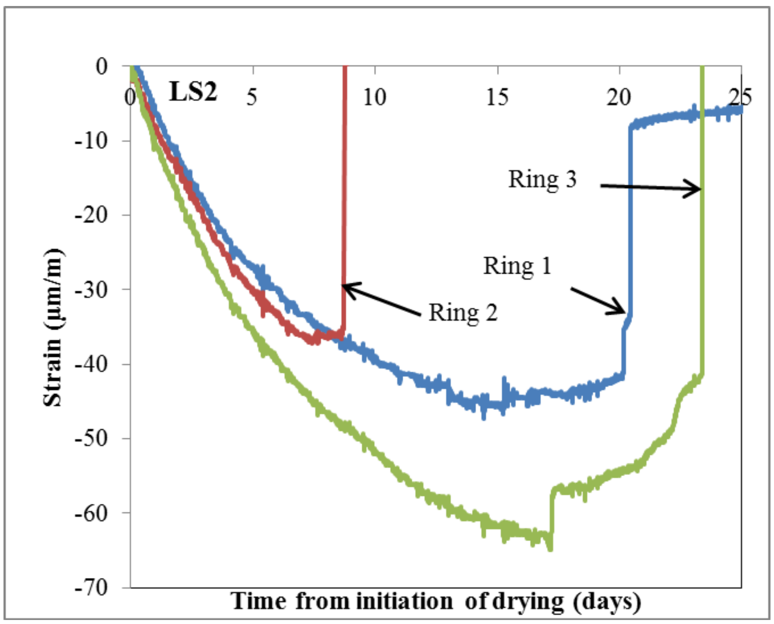

Figure 4.11: Restrained ring data for LS2

4.3.3 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 shown in the strain data was consistent with visual inspection.

The crack widths were notably reduced when compared to the HPC control mixture. On average mixtures with fibers showed a crack width of 0.006 in compared to 0.029 in for the HPC control. This suggests that the use of blended synthetic fibers controls cracking and minimizes the chances of future durability concerns. Shown in Table 4.4 are the largest crack widths measured for each mixture.

Table 4.4: Crack widths (in)

Mixture	Ring 1	Ring 2	Ring 3	Average
HPC Control	0.035	0.020	0.031	0.029
FHPC D5	0.005	0.007	0.007	0.007
FHPC D7.5	0.008	0.005	0.005	0.007
FHPC D10	0.005	0.005	0.005	0.005

The reduction in crack width is likely due to the restraint provided by the blended synthetic fibers once the tensile stress in the concrete from drying surpasses the tensile capacity. The average crack widths of the fiber mixtures were similar, which suggests that there was adequate fiber distribution to minimize the crack widths at all dosages.

4.4 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 not show severe signs of degradation over the 300 cycles. RDME results are shown below in Figure 4.12.

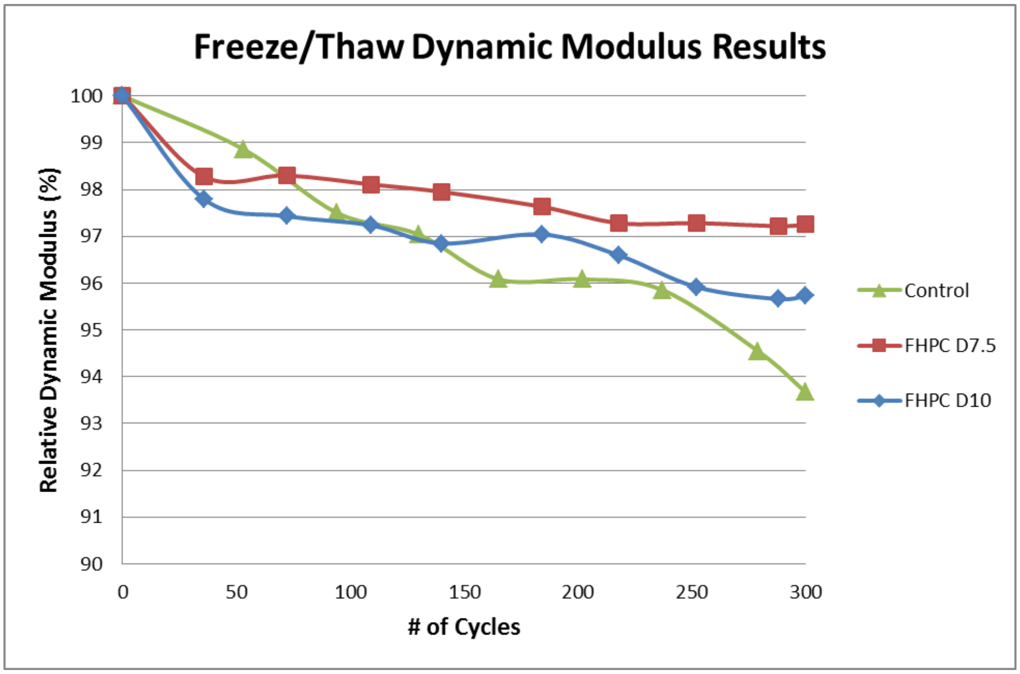

Figure 4.12: Relative Dynamic Modulus of Elasticity Results

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 4.5 below.

Table 4.5: 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 4.13 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 4.13: 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 4.14 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 was observed.

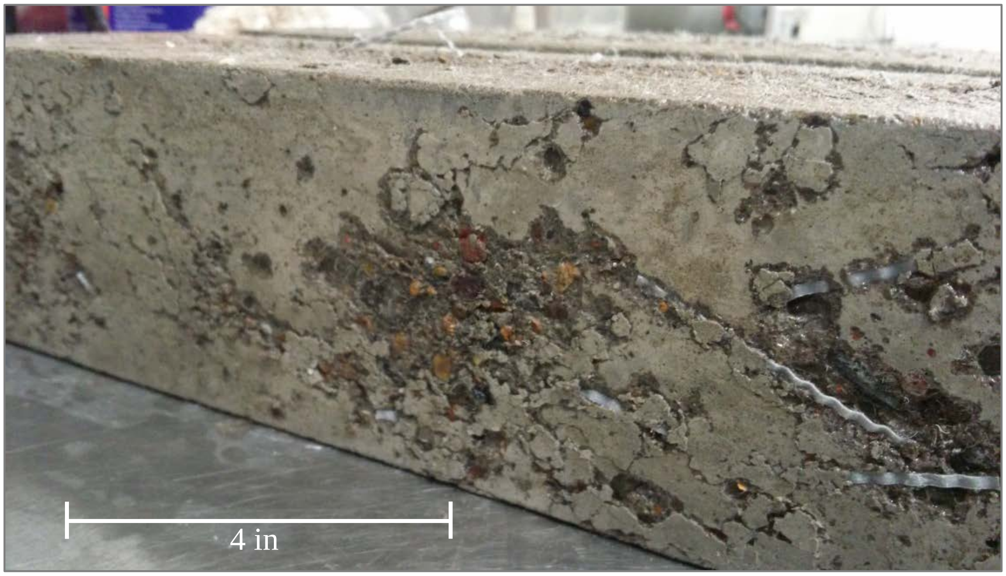

Figure 4.14: FHPC D10 specimen after 300 cycles

Although the fibers may lead to increased scaling during freezing and thawing there was no significant cracking observed, and the RDME was maintained at a higher percentage than the control. The damage shown in figures Figure 4.13 and Figure 4.14 is only on the surfaces of the specimens. The 7.5lb/yd3 fiber dosage rate showed the best 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 provided 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). 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)*.

4.5 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 4.6 is the total charge passed over the 6-hour duration of the RCPT.

Table 4.6: Total charge passed (RCPT)

Mixture ID	Total Charge Passed (Coulombs)
Control	860
FHPC D7.5	560
FHPC D10	693

Although all samples were 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 *(Narayan 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:

- For specimens 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) had a minimal impact on the 90-day drying shrinkage of high performance concrete specimens compared to the control.

- For specimens wet cured for only 3 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 slight increase in the 90-day drying shrinkage of high performance concrete specimens compared to the control.

- 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 as well as crack widening once they initiate. However, the fiber mixtures showed little to no reduction in stress rate when compared to the HPC control mixture.

- In restrained ring testing the HPC control mixtures showed average crack widths of 0.035 in. In all mixtures containing fibers, the crack widths were significantly reduced to 0.005-0.008 in.

- 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 superficial 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 lowered the compressive strength as much as 25% below the 4000 psi minimum threshold and did not reduce free shrinkage.

- The HPC mixture using siliceous crushed river gravel ¾"MSA showed a significant reduction in stress rate and increased the time-to-cracking. This suggests that coarse aggregate angularity may reduce the cracking risk of HPC.

- The use of limestone coarse aggregate most significantly reduced both the drying shrinkage and cracking risk.

5.2 RECOMMENDATIONS

The results of this research support that the incorporation of fibers into high performance concrete increased the time-to-cracking in restrained ring testing and also reduced crack widths and propagation once cracking did occur in the HPC. Further, the incorporation of fibers into high performance concrete mixtures have the potential to reduce both early and later-age cracking for ODOT bridge decks which should be verified through field observation. 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 reducing crack propagation and widening once cracking formed, as well as increasing the time-to-cracking in ASTM 1581 (restrained ring) testing. 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) promoting long-term durability. 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), previous research showed that a crushed limestone aggregate also had superior cracking resistance compared to the HPC control with 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. An investigation on the effect of GGBS to reduce the cracking risk of HPC is suggested. To determine the effect of fiber dosage on the crack widths on the rings specimens an aggressive testing regime is suggested. The rings should only be cured for 1 day and immediately exposed to drying. This will cause higher drying shrinkage stresses and cause the rings to crack sooner. The crack widths in each ring can be monitored thereafter. It is predicted that under higher stresses the crack widths be more pronounced, and the effect of the fiber dosage will be more prominent.

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APPENDIX A – TESTING RESULTS SUMMARY

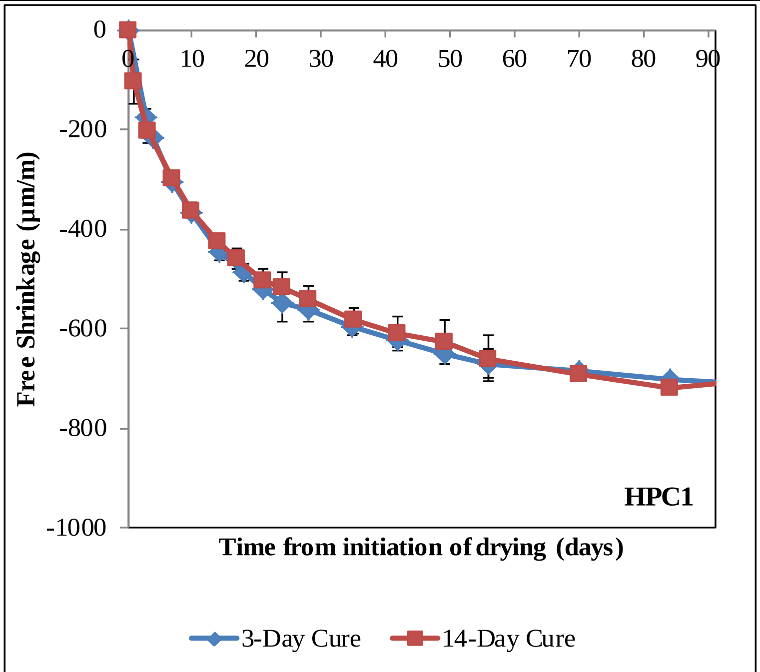
Mix ID:	HPC1	Cast date:	4/4/2012	Curing time (days):	14
Mix description:	ODOT HPC control mix				

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

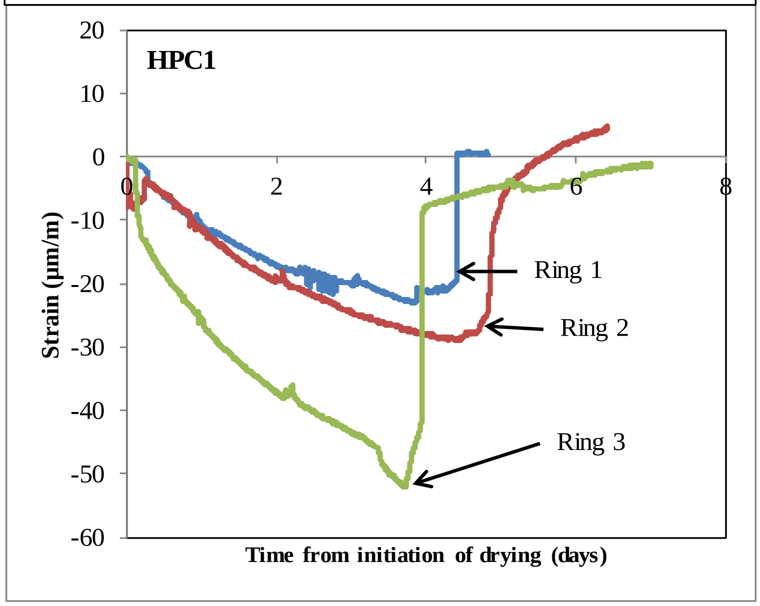
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (psi)	ft (psi)	E (ksi)
5126	588	4679	5787	638	4449



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**	

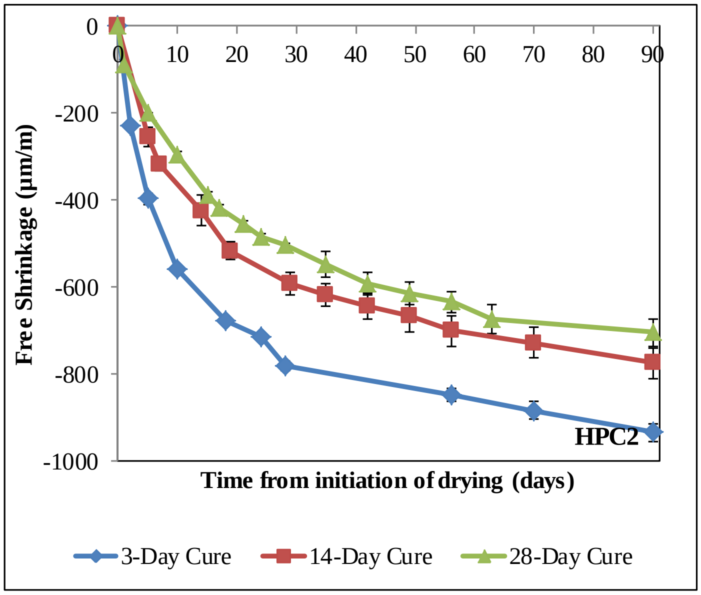
Mix ID:	HPC2	Cast date:	7/10/2013	Curing time (days):	14
Mix description:	ODOT HPC Control: 30% Slag and 4% Silica Fume replacement				

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

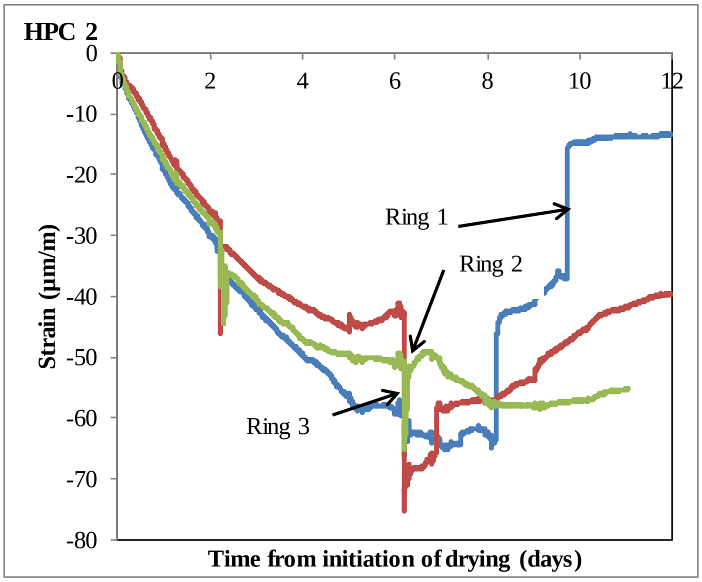
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
4615	485.00	4187.0	-	-	-



Drying Shrinkage (µm/m)

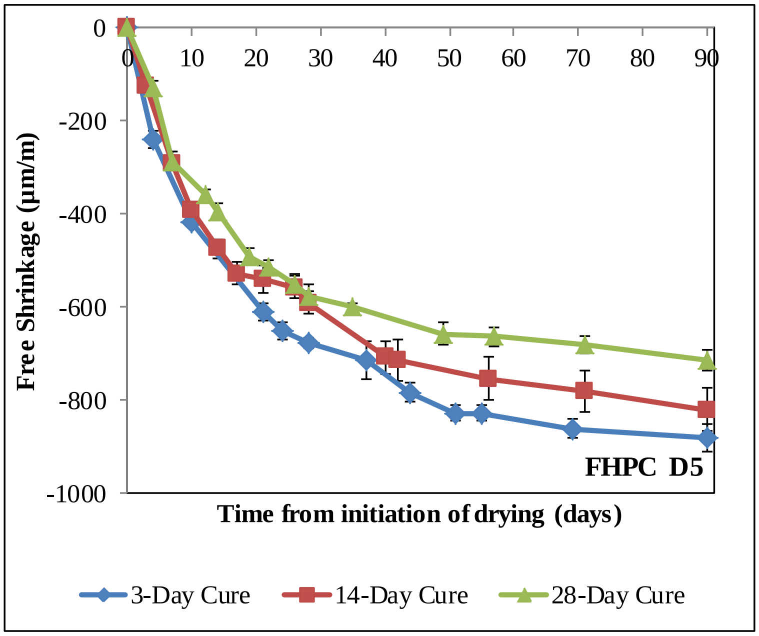
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-397	-253	-87
7	-	-317	-200
10	-557		-293
14	-	-423	-387
21	-	-517	-453
28	-780	-590	-503
42	-	-643	-590
56	-847	-700	-633
70	-883	-727	-
90	-933	-773	-703

**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**	

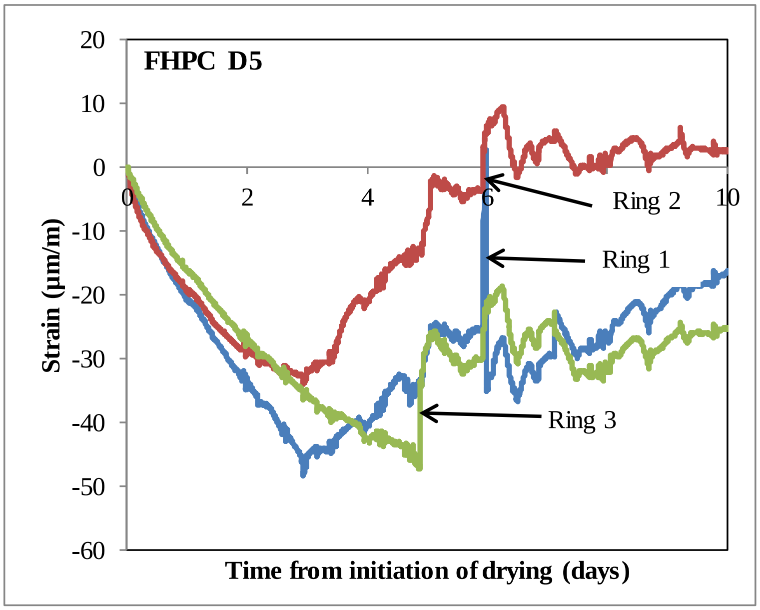
Mix ID:	FHPC D5	Cast date:	5/22/2013	Curing time (days):	14
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 5lb/yd^3				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	22
Slump (in):	2.5	Air content (%):	6.2	Unit weight (pcf):	143
Hardened properties					
28 day standard 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)

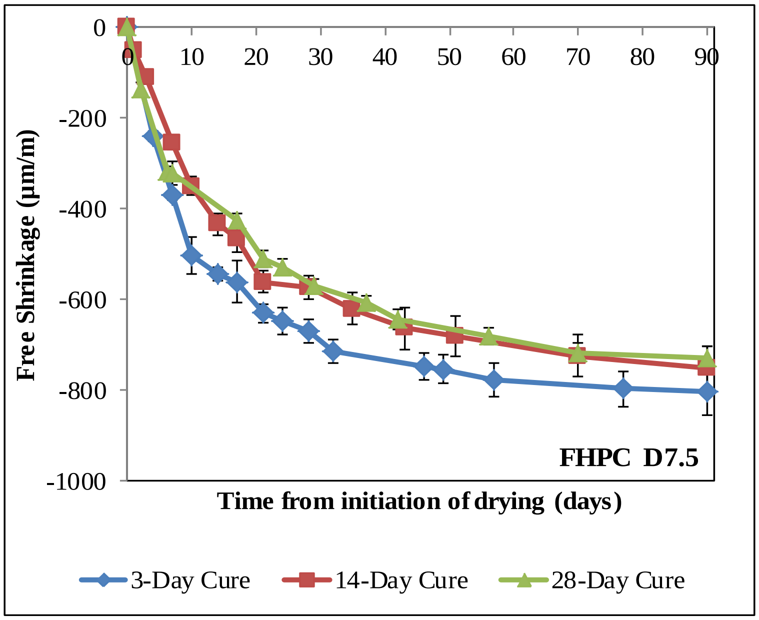
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-240	-123	-130
7	-417	-290	-287
10	-610	-390	-357
14	-650	-473	-393
21	-610	-540	-513
28	-650	-590	-577
42	-677	-713	-
56	-827	-753	-663
70	-860	-780	-680
90	-880	-820	-713

**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**	

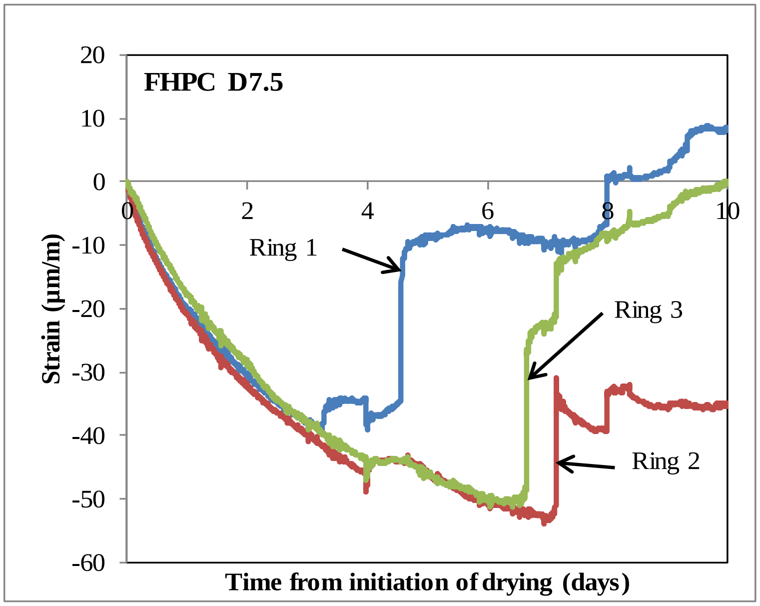
Mix ID:	FHPC D7.5	Cast date:	8/28/2012	Curing time (days):	14
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 7.5lb/yd^3				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	24
Slump (in):	5.5	Air content (%):	7.0	Unit weight (pcf):	140
Hardened properties					
28 day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

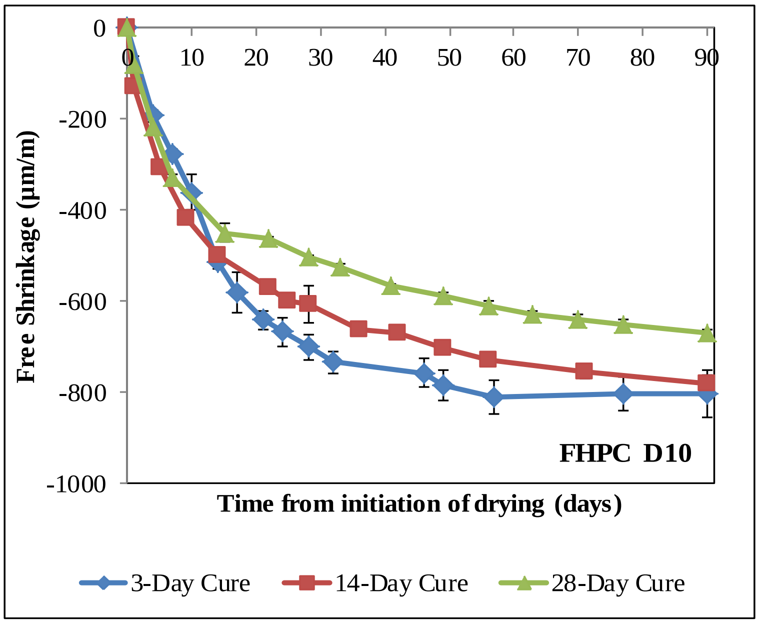
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-240	-50	-137
7	-370	-110	-317
10	-503	-253	-320
14	-543	-350	-393
21	-630	-433	-510
28	-670	-573	-573
42	-747	-663	-663
56	-777	-680	-680
70	-797	-723	-717
90	-803	-750	-727

**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	
Ring 2	7.1	51	**H**
Ring 3	6.6	53	
Average	**6.1**	**52**	

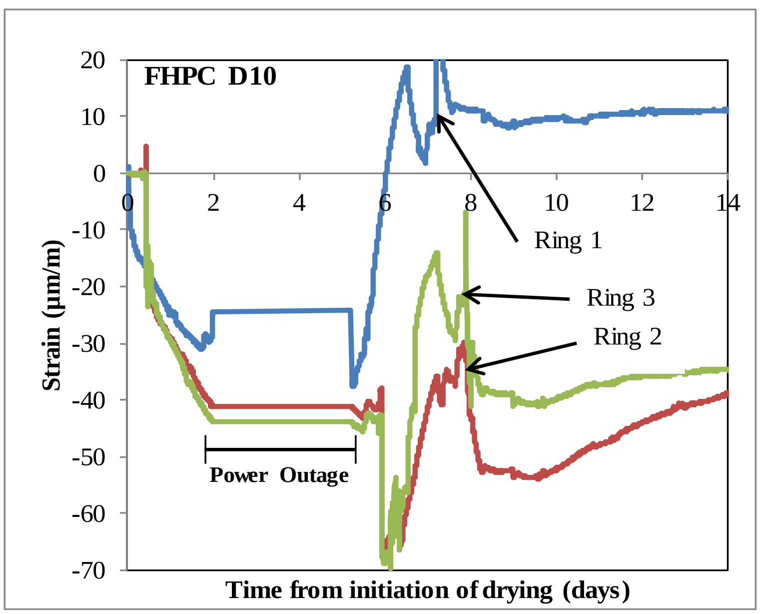
Mix ID:	FHPC D10	Cast date:	7/10/2013	Curing time (days):	14
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 10lb/yd^3				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	20
Slump (in):	3	Air content (%):	6.0	Unit weight (pcf):	143
Hardened properties					
28 day standard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

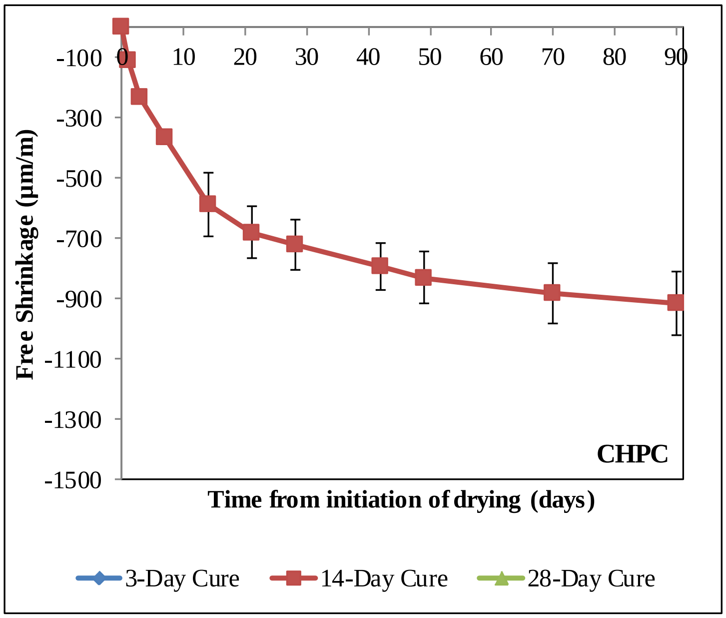
Approx. Time (Days)	3day Cure	14day Cure	28day Cure
0	0	0	0
4	-190	-130	-217
7	-277	-307	-330
10	-360	-417	-
14	-513	-500	-450
21	-640	-570	-463
28	-700	-607	-503
42	-757	-670	-567
56	-810	-727	-610
70	-803	-753	-640
90	-803	-780	-670

**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**	

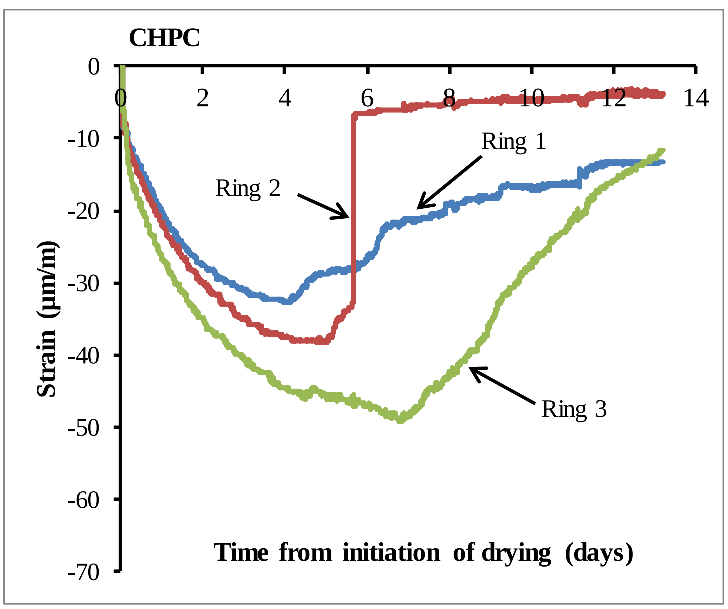
Mix ID:	CHPC	Cast date:	12/19/2013	Curing time (days):	14
Mix description:	ODOT HPC w/ Crushed Coarse 3/4" MSA				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	22
Slump (in):	3.3	Air content (%):	7.5	Unit weight (pcf):	139
Hardened properties					
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
3599	412	4103	3920	345	3793



Drying Shrinkage (μm/m)

Approx. Time (Days)	14day Cure
0	0
4	-110
7	-230
10	-365
14	-
21	-680
28	-720
42	-795
56	-
70	-880
90	-915

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



	ToC (days)	Stress Rate (psi/day)	Crack Risk Rating
Ring 1	9.0	37	**High**
Ring 2	5.7	32	
Ring 3	9.0	38	
Average	**7.9**	**36**	

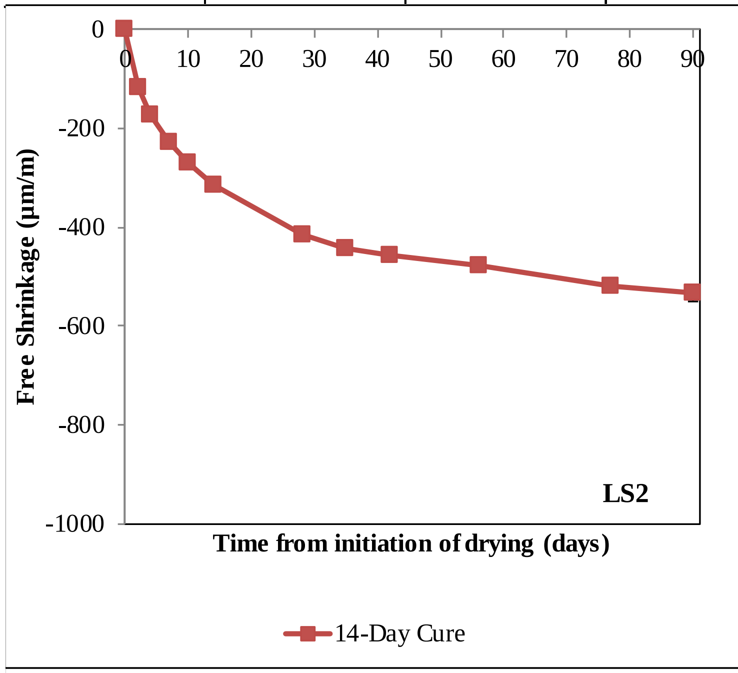
Mix ID:	LS2	Cast date:	2/13/2014	Curing time (days):	14
Mix description:	HPC mixture using crushed limestone as a coarse aggregate				

Fresh properties

Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	19
Slump (in):	2.5	Air content (%):	5.2	Unit weight (pcf):	145

Hardened properties

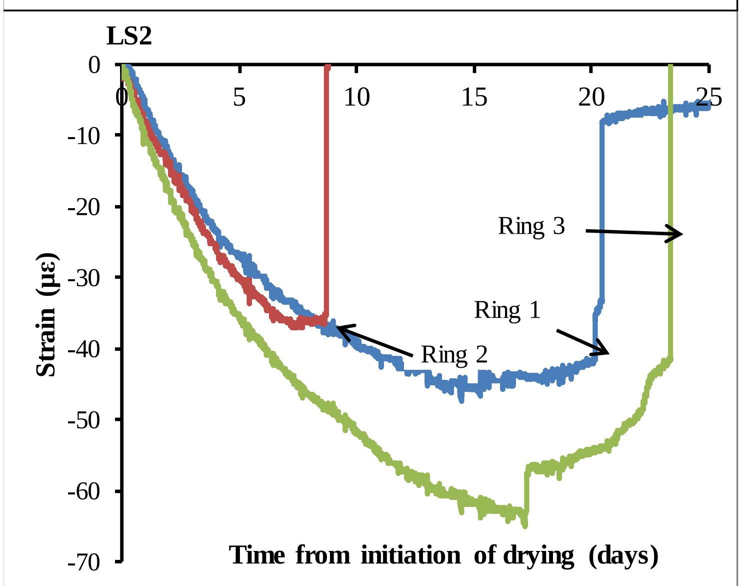
28 day standard cure			28 day matched cure		
fc (psi)	ft (psi)	E (ksi)	fc (psi)	ft (psi)	E (ksi)
5710	529	4411	6069	610	4745



Drying Shrinkage (μm/m)

Approx. Time (Days)	14day Cure
0	0
4	-173
7	-227
10	-270
14	-313
21	-
28	-413
42	-457
56	-477
70	-
90	-533

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



	ToC (days)	Stress Rate (psi/day)	Crack Risk Rating
Ring 1	20.5	21	ML
Ring 2	8.7	31	
Ring 3	23.4	18	
Average	**17.5**	**23**	

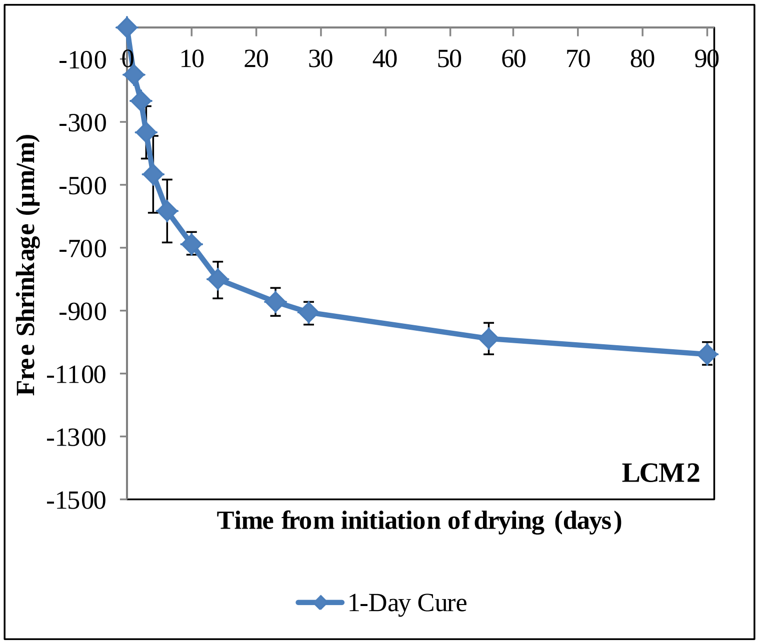
Mix ID:	LCM2	Cast date:	10/5/2012	Curing time (days):	14
Mix description:	Low Cement Content (550lb/yd^3) HPC Mix				

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

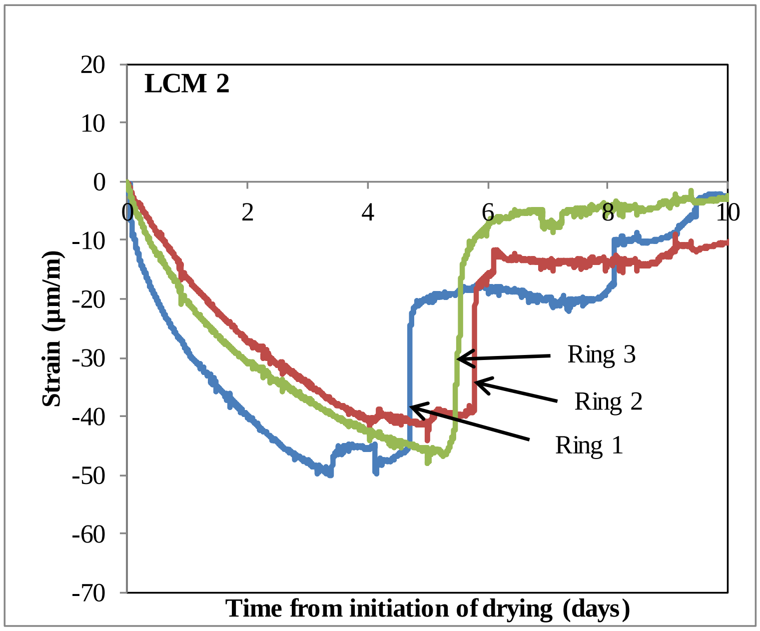
Hardened properties

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)

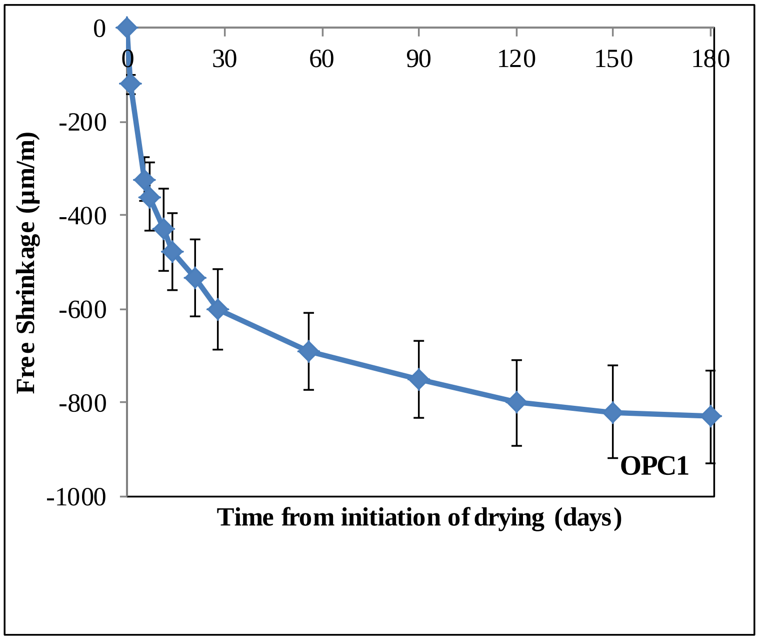
Approx. Time (Days)	1 day Cure
0	0
1	-150
2	-230
3	-330
4	-465
6	-580
10	-685
14	-800
28	-905
56	-985
90	-1035



	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**	

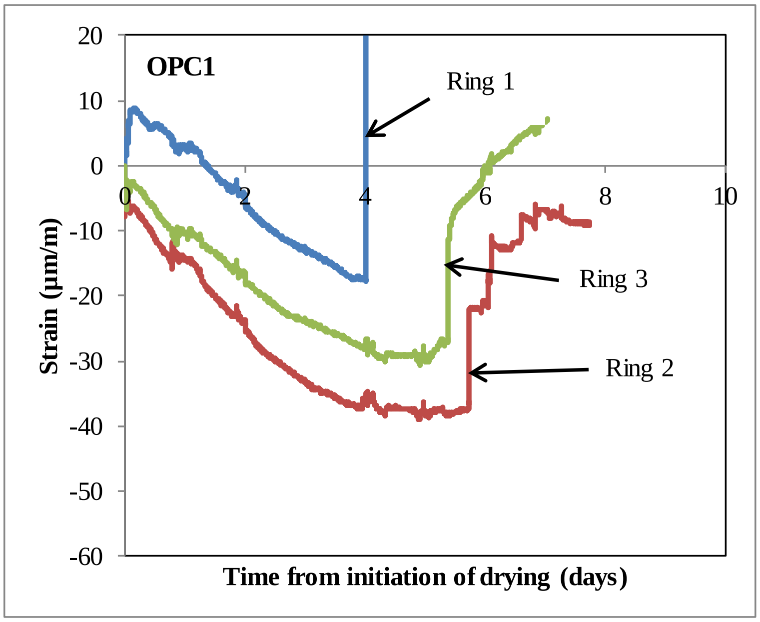
**Ring were cured for 14 days

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**	

Crack Width Measurements in ASTM C 1581 Testing, HPC Control and 5, 7.5 and 10 lbs/yd^3 of fiber addition.

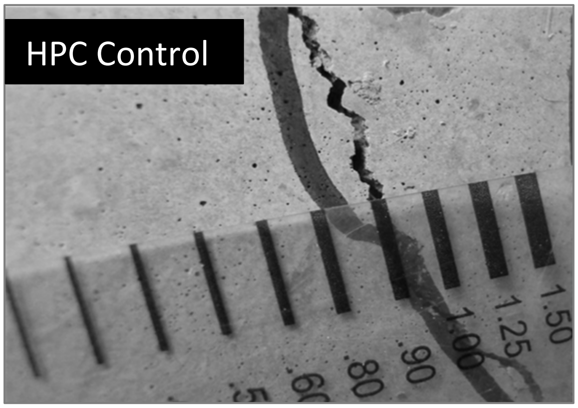


Figure A.1 Crack width- 0.020in - 0.035in

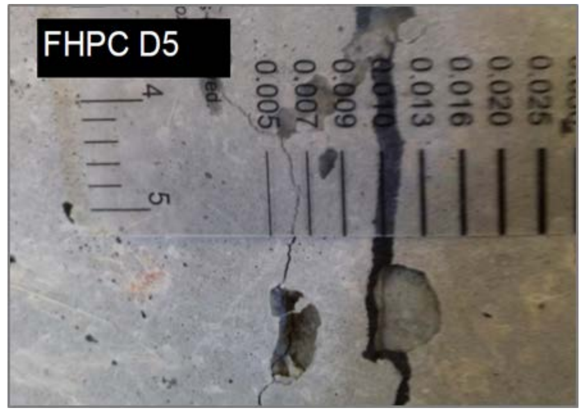


Figure A.2: Crack width- 0.005in-0.007in

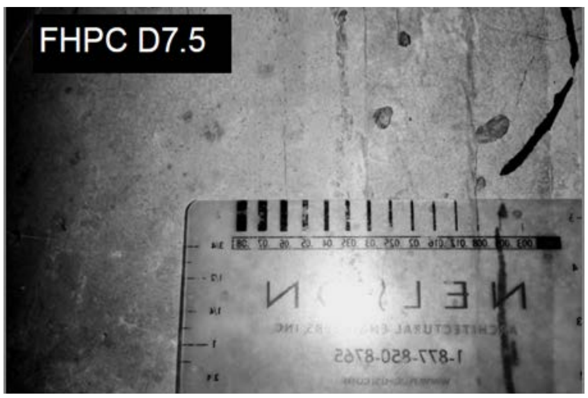


Figure A.3: Crack width- 0.005in-0.008in

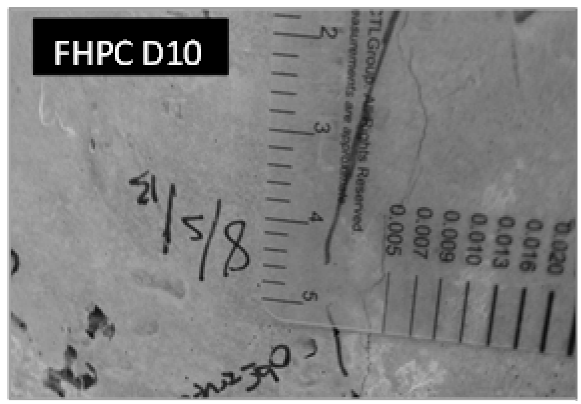
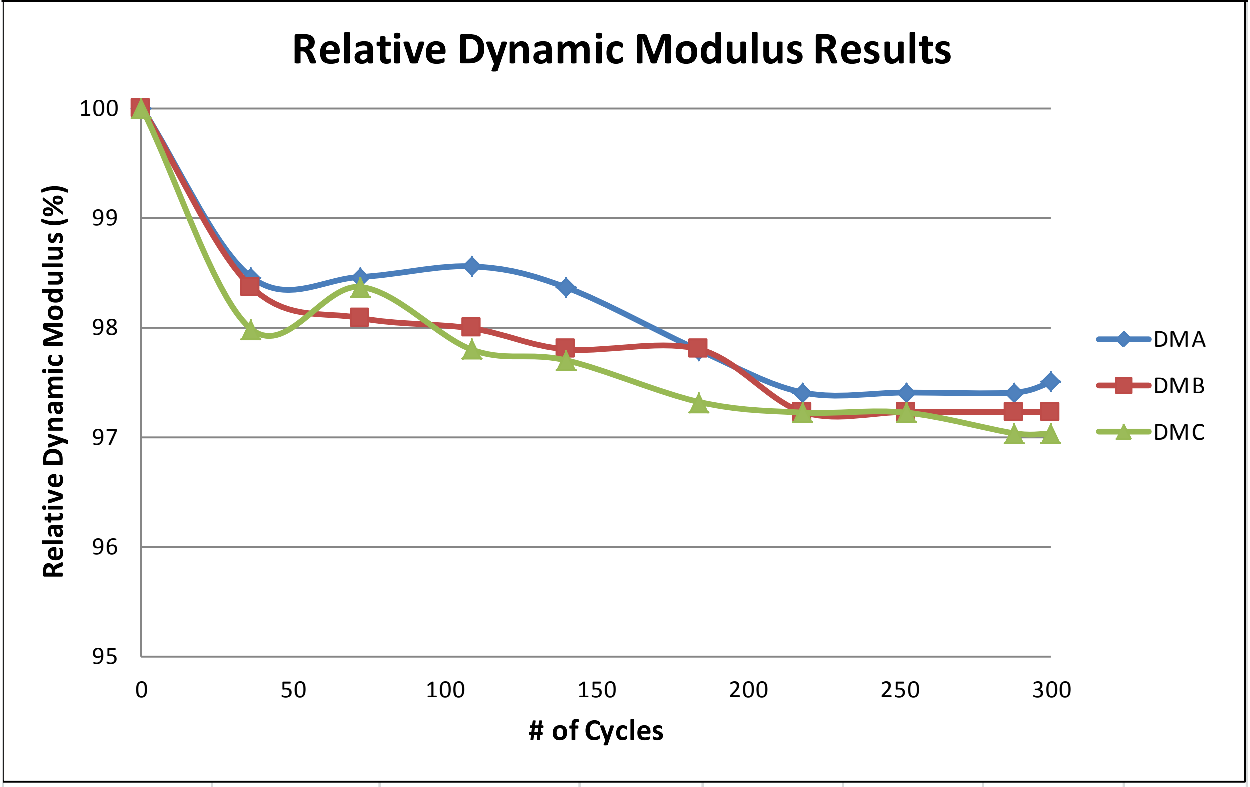
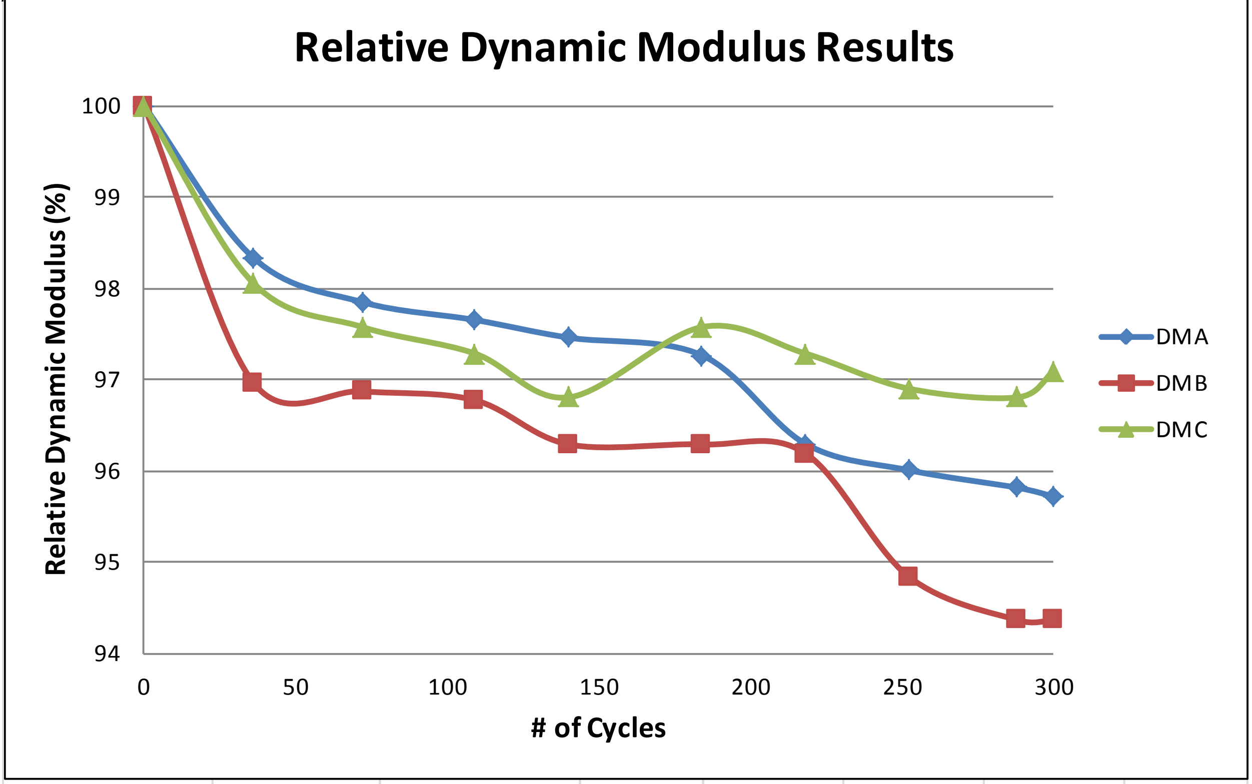


Figure A.4: Crack width- 0.005in

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



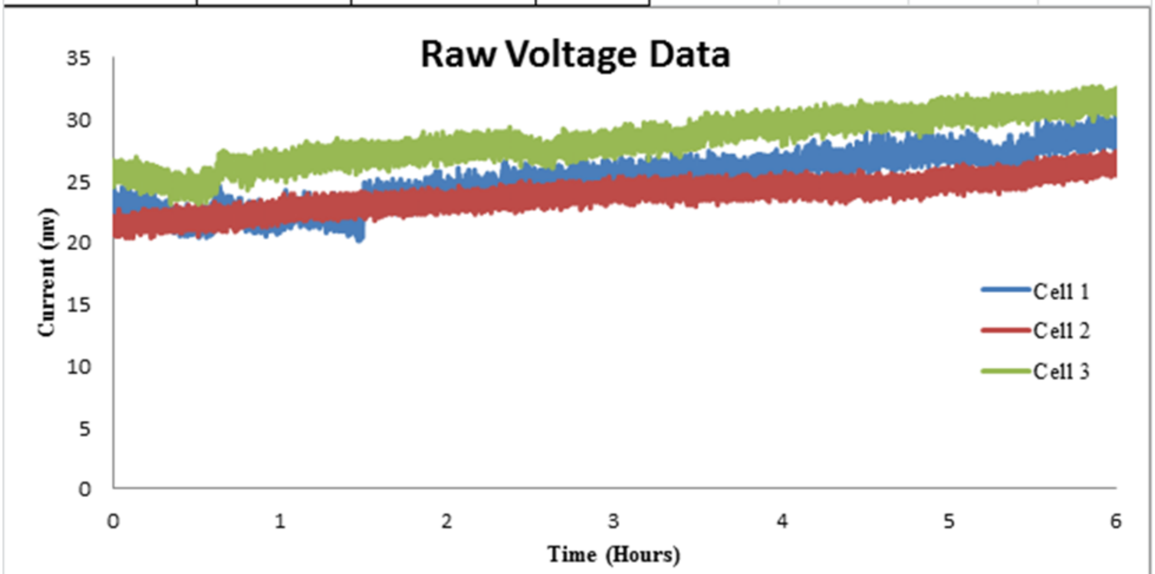
Mix ID:	FHPC D7.5	Cast date:	8/28/2012	Curing time (days):	56
Mix description:	Synthetic Blended Fiber Mix: Dosage Rate 7.5lb/yd^3				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	24.0
Slump (in):	5.5	Air content (%):	7.0	Unit weight (pcf):	140.0

Manual Recordings

Time (Hours)	Cell 1	Cell2	Cell 3
0.0	23.7	22.1	25.9
0.5	22.1	22.6	24.9
1.0	22.7	23.3	26.4
1.5	23.9	23.7	27.0
2.0	24.7	24.0	27.6
2.5	25.4	24.4	25.5
3.0	25.8	24.9	28.1
3.5	26.4	25.1	29.3
4.0	26.6	25.2	29.5
4.5	27.3	25.2	30.1
5.0	27.8	25.7	30.4
5.5	27.8	26.3	31.1
6.0	29.3	27.1	31.6

Total Charge Passed (Coulombs)

Cell 1	545
Cell 2	519
Cell 3	617
Average	**560.34717**



Mix ID:	FHPC D10	Cast date:	7/10/2013	Curing time (days):	56
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):	20.0
Slump (in):	3	Air content (%):	6.0	Unit weight (pcf):	143.0

Manual Recordings

Time (Hours)	Cell 1	Cell2	Cell 3
0.0	29.1	26.0	26.2
0.5	27.1	27.5	26.2
1.0	29.8	28.4	28.2
1.5	31.8	29.9	28.9
2.0	32.2	31.1	30.0
2.5	32.6	31.7	30.3
3.0	33.5	32.2	30.6
3.5	34.2	33.4	31.2
4.0	35.4	33.9	31.6
4.5	35.8	34.5	31.9
5.0	37.2	35.3	31.6
5.5	38.4	35.8	32.4
6.0	39.2	36.2	33.7

Total Charge Passed (Coulombs)

Cell 1	714.65
Cell 2	681.35
Cell 3	684
Average	**693**

**Cell 3 calculated from manual entries