DEVELOPMENT OF SHRINKAGE LIMITS AND TESTING PROTOCOLS FOR ODOT HIGH PERFORMANCE CONCRETE

Final Report

SPR 728

Oregon Department of Transportation

DEVELOPMENT OF SHRINKAGE LIMITS AND TESTING PROTOCOLS FOR ODOT HIGH PERFORMANCE CONCRETE

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Washington, DC 20590-0003

December 2013

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-OR-RD-14-09		

4. Title and Subtitle

Development of Shrinkage Limits and Testing Protocols for ODOT High Performance Concrete

5. Report Date

-December 2013-

6. Performing Organization Code

7. Author(s)

Jason H. Ideker, PhD; Tengfei Fu, PhD, LEED GA; and Tyler Deboodt, MSCE

8. Performing Organization Report No.

9. Performing Organization Name and Address

Oregon Department of Transportation
Research Section
555 13th Street, Suite 1
Salem, OR 97301

10. Work Unit No. (TRAIS)

SPR 728

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

Oregon Department of Transportation
Research Section
555 13th Street, Suite 1
Salem, OR 97301

and

Federal Highway Administration
400 Seventh Street, SW
Washington, DC 20590-0003

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

ODOT has 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 ODOT. 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. However, appropriate shrinkage limits and standard laboratory/field tests that allow proper criteria to ensure crack-free or highly cracking-resistant high performance concrete are not clearly established either in the technical literature or in specifications. The purpose of this research was to provide shrinkage threshold limits for specifications and to provide a robust test procedure that allows easy determination of compliance with specified threshold limits. It has been shown that the "restrained ring" tests are the most comprehensive accelerated laboratory tests to accurately identify cracking potential. In addition, acceptable correlation between the ring test and the field test has been observed and documented. However, a simplified yet robust test procedure is in demand from materials suppliers and Departments of Transportation. Analysis of data obtained from this research project showed that the ratio of free shrinkage to shrinkage capacity (theoretical strain related to tensile strength and modulus of elasticity), referred to as a cracking potential indicator (CPI), was a promising assessment of cracking resistant performance. In this way, only the free shrinkage test (ASTM C157) and basic mechanical properties (ASTM C39, C469 and C496) are required to assess cracking risk of candidate high performance concrete mixture designs. This research investigation showed that a CPI less than 3.0 indicated low cracking risk when correlated to standard restrained ring tests. For ODOT HPC concrete bridge deck mixtures, a limit of 450 microstrain for free shrinkage at 28 day from initiation of drying is recommended to achieve satisfactory cracking resistance. Correlation to field experience is also recommended if these recommended thresholds/limits are adopted by ODOT.

17. Key Words	18. Distribution Statement
CONCRETE, SHRINKAGE, CRACKING, SHRINKAGE LIMIT	Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	87	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

Special thanks to James Batti, and Manfred Dittrich for their help fabricating and setting up equipment for experimentation. David Rodriguez and Jose Banuelos, thank you for your help with preparation and monitoring of specimens. We also want to thank the TAC for this project for their support, valuable insights and genuine interest in the success of the project.

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1.0 INTRODUCTION

1.1 PROJECT BACKGROUD

In the field of civil infrastructure, bridge decks have been widely constructed using high performance concrete (HPC). Concrete bridge decks demand qualities such as low permeability, high abrasion resistance, superior durability, and long design life. To meet these requirements, a high performance concrete (HPC) mixture design has been specified for bridge decks by the Oregon Department of Transportation (ODOT). This mixture design and its durability requirements are outlined in *2008 Oregon Standard Specifications for Construction* (*ODOT 2008*). This particular HPC mixture design includes a low water to cementitious materials ratio (w/cm) of no more than 0.40 and incorporates a ternary blend using ordinary portland cement (OPC) and two supplementary cementitious materials (SCMs): class F fly ash and silica fume. However, features of the HPC mixture design make the HPC bridge decks inherently susceptible to shrinkage and increased cracking risk. In the field, ODOT has observed varying degrees of cracking in concrete bridge decks, especially within the first year of the placement.

At early age, HPC is prone to autogenous shrinkage, plastic shrinkage, drying shrinkage and sometimes thermal volume changes, due to the immature skeleton structure in the cement paste being unable to resist the stress generated by these volume changes. Internal curing, as the name suggests, refers to a technique that cures the concrete from the inside out, by incorporating reservoir water through curing agents, such as pre-wetted fine lightweight aggregate (FLWA) and/or superabsorbent polymers (SAP). It has been proven effective to mitigate early age cracking and has gradually moved from laboratory experiments to field applications. (*Bentz and Snyder 1999, Lura, Jensen et al. 2003, Bentz 2007, Cusson and Hoogeveen 2008, Wei and Hansen 2008, Henkensiefken et al. 2009, Sahmaran et al. 2009*)

At later age, there are many factors that can lead to cracking in HPC bridge decks, including drying shrinkage, creep (sometimes beneficial), environmental fluctuations, loading and restraint conditions. In fact, more than 100,000 bridge decks in this country have suffered from transverse cracking (*Krauss and Rogalla 1996*), which is a pattern indicating the presence of drying shrinkage. Over the past 40 years, most of the above-mentioned causes of cracking in concrete bridge decks have been well identified and documented through laboratory research and field experience. Furthermore, proper mixture modifications and construction practices have been developed to minimize the risk of cracking. Nevertheless, concrete still exhibits cracking during its service life and as a result this continues to be a significant research thrust by many agencies.

Cracking of high performance reinforced concrete structures, in particular bridge decks, is of concern to ODOT. Cracking at early ages (especially within the first year after placement) results in additional costs and a significant maintenance burden to ODOT. These added costs can be avoided through improved testing techniques, improved material specifications, and improved construction requirements related to reducing cracking risks in such structures. A significant challenge to overcoming cracking risk is to reduce the shrinkage and, ultimately, the stresses generated as a result of such shrinkage in concrete mixtures. A commonly agreed upon testing method and subsequent shrinkage threshold limits will help ODOT to achieve a higher degree confidence in specifying and receiving crack-free concrete.

1.2 RESEARCH SCOPE

This report consists of a focused literature review on recent research work on bridge deck cracking and testing results supporting a proposed "cracking potential indicator" (CPI) criteria. This research project (SPR 728) is closely related to SPR 711 Internal Curing of Concrete Bridge Decks, which was completed in 2011.

The objectives of the research project are listed as follow:

- Understand how mechanical properties along with free shrinkage affect high performance concrete cracking potentials;

- Analyze and identify a drying shrinkage threshold limit/criteria for HPC bridge decks to ensure high cracking-resistance concrete, and;

- Develop a simple testing procedure for the above limit/criteria that can be easily applied by contractors or materials suppliers.

2.0 LITERATURE REVIEW: RECENT RESEARCH ON BRIDGE DECK SHRINKAGE/CRACKING

In 2010, the United States (US) Federal Highway Administration (FHWA) reported that 27% of the country's bridges in the National Highway System were considered "structurally deficient" or "functionally obsolete"(*U.S. Department of Transportation 2010*). According to the most recent 2013 Report Card for America's Infrastructure by American Society of Civil Engineers (ASCE), In 2012, about 11% of the nation's bridges were classified as "structurally deficient", which refers to bridges having major deterioration, cracks, or other deficiencies in their structural components including decks, girders, or foundations (*ASCE 2013*). According to a survey conducted by Krauss and Rogalla (*Krauss and Rogalla 1996*) in 1996, 62% of respondents in the US departments of transportation (DOTs) believed transverse cracking was a significant problem. More than 100,000 bridges decks had suffered from transverse cracking, which is a pattern indicating the presence of drying shrinkage. However, there are many factors that can lead to cracking in concrete bridge decks, such as concrete dimensional stabilities (shrinkage and creep), environment fluctuations and restraint conditions. Cracking is determined by the competition between strength gain of the materials and the development of tensile stress, which is mainly due to restraint provided by the structural elements. Over the past 40 years, most of the causes of cracking in concrete bridge decks have been well identified and documented through laboratory research and field experience. Furthermore, proper mixture modifications and construction practices have been developed to minimize the risk of cracking. Nevertheless, concrete still exhibits cracking during its service life.

2.1 ASTM INTERNATIONAL STANDARDS

The restrained ring test has been used by a number of researchers since the 1940's (*Carlson 1942*, *ACI Committee 231 2010*). It is a practical tool to evaluate cracking risk of concrete and mortar. It was not until a few decades ago that quantitative analysis of this test has come into existence by implementing strain gauges to qualify the stress state of the cementitious specimens (*ACI Committee 231 2010*). Weiss (*Weiss 1999*) made contributions to the stress distribution analysis in the ring using a nonlinear fracture mechanics model. Later, See et al. (*See et al. 2004*) investigated a wide range of modern concrete and mortar mixtures using a specific ring test (Figure 2.1), which was later adopted by ASTM as a standard testing method. Based on the results, they suggested a cracking potential classification (as shown in Table 2.1) on the basis of either time-to-cracking or stress rate development in the concrete ring specimen. This classification was also adopted by ASTM C1581.

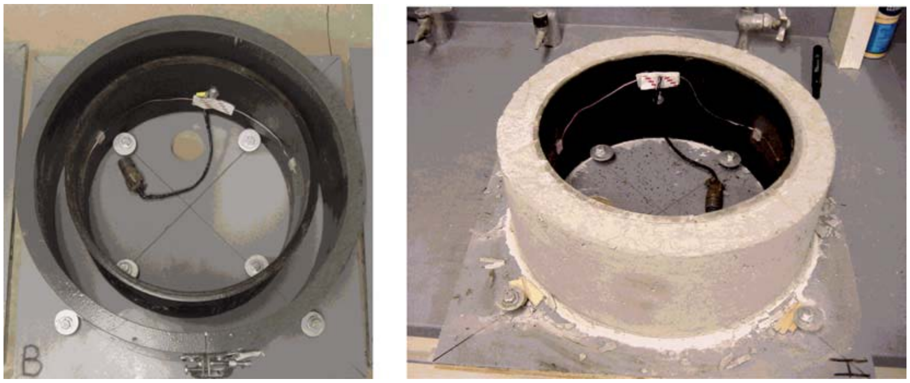

Figure 2.1: ASTM test specimen mold (left) and test specimen (right) (*See et al. 2004*)

Table 2.1: Cracking potential classification (Based on stress rate at time-to-cracking). (*See et al. 2004, ASTM C1581 2004*)

Time-to-Cracking, t_{cr}, Days	**Stress Rate at Cracking, S, MPa/Day**	**Potential for Cracking**
$0 < t_{cr} \leq 7$	$S \geq 0.34$	High
$7 < t_{cr} \leq 14$	$0.17 < S < 0.34$	Moderate-High
$14 < t_{cr} \leq 28$	$0.10 < S < 0.17$	Moderate-Low
$t_{cr} > 28$	$S < 0.10$	Low

Time-to-cracking is the difference between the age at cracking and the age drying was initiated. It can be used to assess the relative cracking performance of specimens that cracked during the test. If not cracked, the stress rate at the age when test was terminated can be compared between tested materials.

2.2 TEXAS DEPARTMENT OF TRANSPORTATION (TXDOT)

From 2002 to 2006, a two-phase project titled "*Evaluation of Alternative Materials to Control Drying-Shrinkage Cracking in Concrete Bridge Decks*" was conducted by TxDOT and the University of Texas, Austin (*Folliard et al. 2003*). The major goal of this project was to identify an effective materials-based method of controlling drying shrinkage.

In the Phase-I of this research, a detailed summary on factors affecting cracking in concrete bridge decks was given in terms of shortcomings in materials, design practices and construction techniques. Common methods of controlling shrinkage cracking were also identified in the literature review section, including conventional and innovative methods. The innovative methods included fiber-reinforced concrete, shrinkage reducing admixtures (SRAs), shrinkage compensating concrete and high-volume fly ash (HVFA), which were all evaluated in laboratory experimentation. To better identify the cracking propensity, a combination of laboratory tests were recommended:

- Free shrinkage prism test (ASTM C157/AASHTO T-160);
- Restrained ring test (ASTM C1581/AASHTO PP34), and;
- Early-age strength properties:
    - Compressive strength test (ASTM C39/AASHTO T-22);
    - Tensile strength test, and (ASTM C496/AASHTO T-198);
    - Modulus of elasticity test (ASTM C469).

Each of these tests by itself was not capable of providing sufficient information to evaluate the propensity for drying shrinkage-induced cracking. Therefore, a number of comprehensive considerations were recommended (*Folliard et al. 2003*). It was recommended that an ideal crack-free or highly crack-resistant mixture should be one showing no cracking in the ring test, having a relatively low free shrinkage strain and early-age modulus of elasticity, and high early-age tensile strength. However, the complicated interaction among all these properties made it very difficult to prescribe a specific free shrinkage limit as a permissible threshold for materials selection. It was also recommended that a mixture with SRA, polypropylene fibers, shrinkage compensating cement, or high volume fly ash could provide the best resistance to drying shrinkage cracking in bridge decks. In the phase-II study, a satisfactory correlation was found between the ring test and large-scale bridge decks (LSBD) cast and monitored at an outdoor exposure site in Austin, Texas. However, to determine the relative susceptibility to drying shrinkage cracking, the ASTM C 157 prism test would be inadequate on its own, and many other recommended tests results should be considered. Table 2.2 gives a summary of free shrinkage and time to cracking for all mixtures. It should be noted that most "no crack in the ring" means no cracking was present after 600 days.

Table 2.2: Shrinkage ring test results (*Brown et al. 2007*)

Mixture	Average time to cracking, days	Free shrinkage strain at 28 days
Laboratory specimens		
Control	38 (34, 36, 43, 39)	0.00032
Type K	No cracks in two rings	0.00009*
HVFA	41 (25, 52, 44)	0.00021
SRA	No cracks in two rings	0.00012
HPC	35 (35, no crack)	0.00023
SF	31 (43, 18)	0.00028
FRC F-I	No cracks in two rings	0.00034
FRC F-II	202 (202, no crack)	0.00031
Phase I LSBD Specimens		
HPC	30 (30, no crack)	0.00033
SRA	No cracks in two rings	0.00017
Phase II LSBD Specimens		
Control	20 (16, 24)	0.00034
HPC	19 (18,19)	0.00030
SRA	No cracks in two rings	0.00018
HVFA	No cracks in two rings	0.00029
Shrinkage-compensating concrete	No cracks in two rings	Not measured
FRC	No cracks in two rings	0.00033

*Shrinkage of Type K mixture was measured according to ASTM C878.

Based on a comprehensive test result, concrete mixtures containing SRAs, polypropylene fibers, shrinkage compensating cement or HVFA were recommended to minimize early-age shrinkage stress and cracking risk (*Brown et al. 2007*).

2.3 VIRGINIA DEPARTMENT OF TRANSPORTATION (VADOT)

A study in 2004 by VaDOT recommended drying shrinkage limits of 0.04% length change at 28 days and 0.05% length change at 90 days for concrete containing SCMs following the ASTM C157 test. For OPC concrete, the limits are set to 0.03% at 28 days, and 0.04% at 90 days. This was done by comparing unrestrained drying shrinkage in the ASTM C157 prisms to restrained cracking tendency in ASTM C1581 testing. However, mixtures with the lowest free shrinkage did not subsequently exhibit the lowest strains in restrained ring testing. Since all of the mixtures performed similarly in this research project (e.g. similar drying shrinkage results and few mixtures cracking) it draws into question the validity of the shrinkage limits purported by the study for mixtures of lower w/c and ternary blends (*Mokarem et al. 2005*).

From 2007 to 2010, a project titled "*Bridge Deck Concrete Volume Change*" was conducted by the Virginia Transportation Research Council (*Ramniceanu et al. 2010*). The goal of this research was to develop a field quality control method for shrinkage and its associated limits. Shrinkage was evaluated at early age (24 hours) and long-term age (180 days) for VaDOT concrete bridge deck mixtures, including ternary blended mixtures (fly ash and microsilica), latex modified mixtures and expansive mixtures. A modified ASTM C157 prism test was used to test early-age shrinkage, and normal ASTM C157 procedures were used to measure the long-term shrinkage. Ring tests, v-notch tests and scaled bridge deck overlays were used to evaluate shrinkage cracking potentials. Based on the test results, the ASTM C157 test method was recommended to VaDOT to control shrinkage of field overlays and general bridge deck mixtures. The shrinkage limits of each current mixture are shown in Table 2.3.

Table 2.3: ASTM C157 Shrinkage Control Limits*, inspired by (*Ramniceanu et al. 2010*)

Age	Overlay Mixtures (microstrain)					A4 Mixtures (microstrain)		
	LMC	RSL	LMK	TRN		A4-FA	A4-S	A4-K
3 Days	300(310)	150(125)	150(125)	400(380)		-	-	-
7 Days	400(395)	250(215)	300(280)	700(670)		250(206)	350(350)	300(273)
28 Days	600(580)	350(295)	400(350)	800(750)		500(370)	500(537)	400(385)

* Values in parentheses are experimental measurements.

In total, there were seven concrete mixtures were tested: a latex modified (LMC), a Type K latex modified (LMK), a Rapid Set® latex modified (RSL), a ternary (fly ash and microsilica, TRN), a fly ash (A4-FA), a slag (A4-S), and a Type K cement (A4-K) mixture. For each mixture and age combination in the table, the shrinkage limit value is shown first and the measured value is shown in parentheses. For example, the measured free shrinkage for standard HPC mixture (TRN) at 28 day was 750 microstrain, while the limit was set for 800 microstrain. However, the restrained ring tests were not in good agreement with the scaled bridge overlay specimens. Nonetheless, the researchers stated that the scaled bridge deck specimen best mimicked field conditions, thus the free shrinkage limits should be linked to the performance of the scaled bridge decks (*Ramniceanu et al. 2010*).

2.4 KANSAS DEPARTMENT OF TRANSPORTATION (KDOT)

In 2005, KDOT's report "*Evaluating Shrinkage and Cracking Behavior of Concrete Using Restrained Ring and Free Shrinkage Tests*" provided a detailed review of previous research efforts on concrete bridge deck cracking. In addition, it also provided a comprehensive review of the ring test including the background of the ring test, different types of ring tests and the effect of ring geometry. Free shrinkage and restrained ring tests were used in this study to evaluate concrete bridge deck mixture designs used within the state. The major conclusions in this study were as follows: (*Tritsch et al. 2005*)

- Using coarser ground (Type II) cements could reduce shrinkage;
- Shrinkage increased with increased paste content;
- Use of a SRA significantly reduced shrinkage;
- Longer curing times were beneficial to reduce shrinkage, and;
- Free shrinkage was found to be a weak predictor of actual restrained shrinkage.

The researchers attempted to correlate free shrinkage with restrained shrinkage rate, but found that the free shrinkage was a weak predictor of actual restrained shrinkage rate. Of 39 restrained ring tests, only one mixture with a high paste content cracked. Such low cracking sensitivity was due to the thickness of the steel ring, which was too thin to provide enough restraint to promote cracking in the surrounding concrete rings (*Tritsch et al. 2005*).

Nevertheless, this study provided guidance to reduce shrinkage and laid the groundwork for the later two-phase pooled fund study "*Construction of Crack-Free Concrete Bridge Decks*", which focused on: (*Lindquist et al. 2008, McLeod et al. 2009*)

- Development of an aggregate optimization and concrete mixture design program;
- Free-shrinkage tests to evaluate potential low cracking HPC (LC-HPC) mixtures;
- Evaluation of the chloride penetration into concrete using long-term salt-ponding tests;
- Specification for LC-HPC construction and standard practices in Kansas, and;
- Construction and preliminary evaluation of LC-HPC bridge decks in Kansas.

The LC-HPC mixture, also usually referred as "KU Mix", has proven effective in reducing cracking in bridge decks by field applications (*Darwin et al. 2010*). Some of the features of this low cracking mixture are listed as follows:

- Optimized aggregate gradation
- Recommended moderate strength 25-30 MPa (3500 – 4500 psi)
- Low cementitious materials content, less than 320 kg/m^3 (540 lb/yd^3)
- Moderate w/cm (0.43-0.45)
- 25mm maximum aggregate size
- Air content of 8±1.5 %
- Low designated slump 40-90 mm (1 ½ - 3 ½ in)
- Controlled construction temperature 13-21 ºC (55 – 70 °F)

2.5 NEW JERSEY DEPARTMENT OF TRANSPORTATION (NJDOT)

New Jersey DOT (NJDOT) performed a research project from 2005 to 2007 to investigate the cracking potential of the HPC mixtures for bridge decks in New Jersey State (*Nassif et al. 2007*). Comprehensive laboratory tests were conducted including compressive strength, splitting tensile strength, modulus of elasticity, free shrinkage, and restrained shrinkage. For restrained shrinkage tests, AASHTO PP34-99 was utilized, with selected modifications to better capture the cracking performance by monitoring the relative displacement within the ring specimen (as shown in Figure 2.2). In addition to the strain gauges attached to the inner surface of the steel ring, six vibrating wire strain gauges (VWSG) were installed to monitor the relative movement in the concrete ring sections. In this way, the actual strain in the concrete could be measured and quantified, which allowed a more accurate comparison between mixtures.

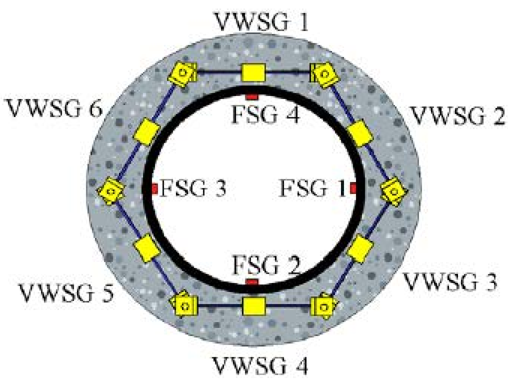

Figure 2.2: Modified AASHTO restrained ring tests setup (FSG: foil strain gauge; VWSG: vibrating wire strain gauge) (*Nassif et al. 2007*).

They found that high coarse aggregate to fine aggregate ratio (over 1.5) with high coarse aggregate content over 1110 kg/m^3 (1875 lb/yd^3) could help significantly reduce cracking potentials. By correlating free shrinkage to restrained shrinkage performance, a free shrinkage limit of 450 microstrain at 56 days was recommended to ensure high cracking resistance for HPC bridge decks.

2.6 WEST VIRGINIA DIVISION OF HIGHWAYS (WVDOH)

Recent research by Ray and co-workers discovered a correlation between material properties (28-day compressive strength and 90-day free shrinkage strain) and time of cracking obtained from the AASHTO ring tests (*Ray et al. 2012*). In this research, 18 different HPC mixture designs with different SCMs and different w/c were investigated. The ASTM C157 test was used to measure free shrinkage strain. AASTHO ring tests were used to obtain cracking potential (time to cracking in the ring). According to the test results, a correlation was established between "cracking index" and time to cracking in the rings. The cracking index was given as $100f^{0.1}\varepsilon^{-1.0}E^{-1.2}$ that incorporated the common material properties free shrinkage strain (ε), compressive strength (f), and modulus of elasticity (E). A data set from representative highway bridge projects was used to determine the cracking threshold, as shown in Figure 2.3. The conclusion was that to be conservative any concrete mixture design with a time to cracking of 30 days or later in the AASHTO ring test would offer acceptable cracking resistance in the field.

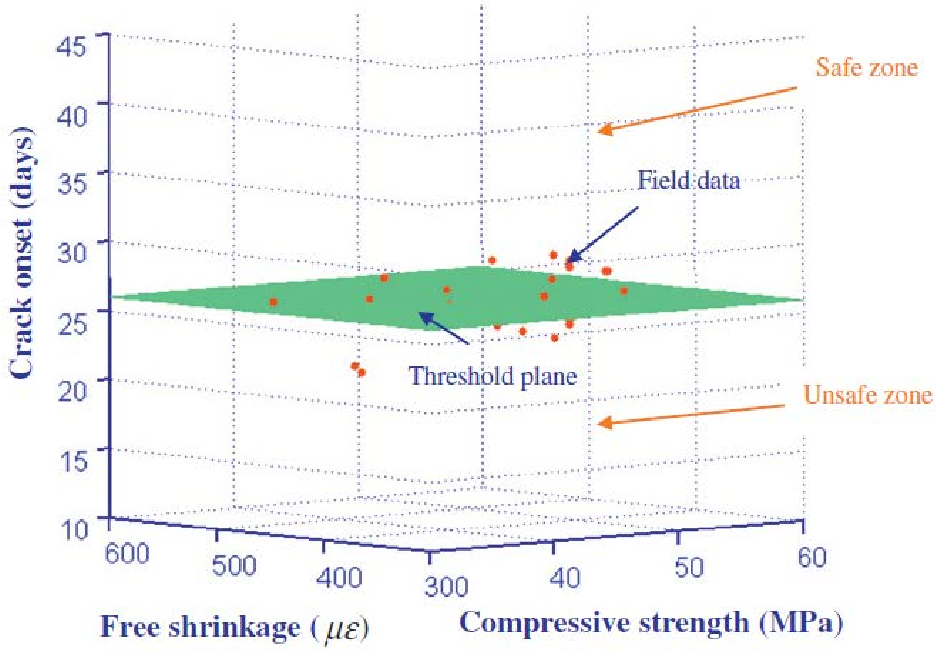

Figure 2.3: Threshold plane of cracking onset based on field data. (*Ray, et al. 2012*)

This research was the first attempt to combine free shrinkage with common materials properties, which provides a more comprehensive understanding of cracking issues in concrete. Although this method still needs to be further confirmed or upgraded, a new perspective was provided in how to determine the laboratory testing threshold limits to minimize cracking risk in the field. Another noticeable contribution of this work was that a simple and feasible modification to the ACI 209 shrinkage model was proposed to more accurately predict shrinkage using local materials.

2.7 WASHINGTON DEPARTMENT OF TRANSPORTATION (WSDOT)

In 2010, WSDOT conducted research with Washington State University titled, "*Mitigation Strategies for Early-Age Shrinkage Cracking in Bridge Decks*". The goal of this research was to identify effective early-age cracking mitigation strategies for concrete bridge decks in Washington State. The research report included a comprehensive literature review and suggested the focus of this study was to identify mitigation methods based on material properties, such as different sources and sizes of aggregates, paste content, cementitious materials including SCMs and SRAs. Free shrinkage and restrained ring tests were performed on 22 mixtures designs including two current WSDOT concrete mixtures. Based on the laboratory evaluations, the major conclusions are listed: (*Qiao et al. 2010*)

- SRAs significantly reduced the free shrinkage and restrained shrinkage cracking tendency of all mixtures;
- Less paste volume due to larger aggregate size reduced free shrinkage and delayed cracking in the ring specimens, and;
- Lower free shrinkage strain, with acceptable flexural strength, generally indicated relatively good restrained shrinkage cracking resistance.

In this study, two different sizes of rings were used for restrained ring testing. This provided different degrees of restraint and could accommodate different sizes of coarse aggregates. Hardened concrete properties, such as compressive strength, splitting tensile strength, flexural strength and modulus of elasticity were tested at 7 days and 28 days. The "KU Mix" was also applied in one of the investigated mixtures. The shrinkage was reduced from 400 microstrain to 150 microstrain at 28 day. The significant differences between the control mixture and the "KU Mix" included: reduced cement content from 440 kg/m3 (743 lb/yd3) 325 kg/m3 (550 lb/yd3) increased maximum aggregate size from 19 mm (3/4 in) to 25 mm (1 in), and optimization of the aggregate gradation.

The authors also attempted to link free shrinkage strain to cracking and determined the concrete cracking resistance was the combination of its tensile strength and its free shrinkage properties. However, no shrinkage limit was proposed. Further field evaluation was needed to verify the link between free shrinkage with restrained cracking and ultimately with field performance (*Qiao et al. 2010*).

2.8 OTHER WORK

Al-Manaseer and coworkers (*Al-Manaseer et al. 2011*) conducted a long-term shrinkage and creep study on high strength concrete (HSC). This work was also supported by the California Department of Transportation (Caltrans). Eighty-one mixtures with different SCMs and superplasticizers were investigated. Free drying shrinkage measurements in cement and concrete samples lasted up to 3000 days. They documented the effect of SCMs (i.e. fly ash, silica fume, slag, and metakaolin), superplasticizers, and especially SRAs on compressive and long-term free drying shrinkage. No cracking evaluation was performed. They found that by incorporating SRAs the shrinkage was significantly reduced. They also found that increasing the SRA dosage above 1.5% had no significant effect on free drying shrinkage.

In 2002 to 2003, Michigan DOT (MDOT) conducted an investigation of causes and methods to minimize early-age deck cracking on Michigan Bridge decks (*Aktan et al. 2003*). A nationwide survey was also conducted as part of the research. The results showed 30 of 31 responding states (as shown in Figure 2.4) reported early-age bridge deck cracking issues, all respondents except Hawaii. Twenty-five states indicated the cracking happened during the first several months after placement, and eleven responded cracking occurred during the first year. The literature review pointed out that main factors influencing bridge deck cracking were restrained volume change due to shrinkage and thermal load, coupled with construction practices. From the field inspection data and laboratory testing, a thermal load of approximately 11ºC (20ºF) was identified to initiate deck cracking. The research team suggested that the hydration temperature rise should be limited in the standard specifications. They also suggested a continuation of this research to develop a specific mixture design for the minimization of thermal loading.

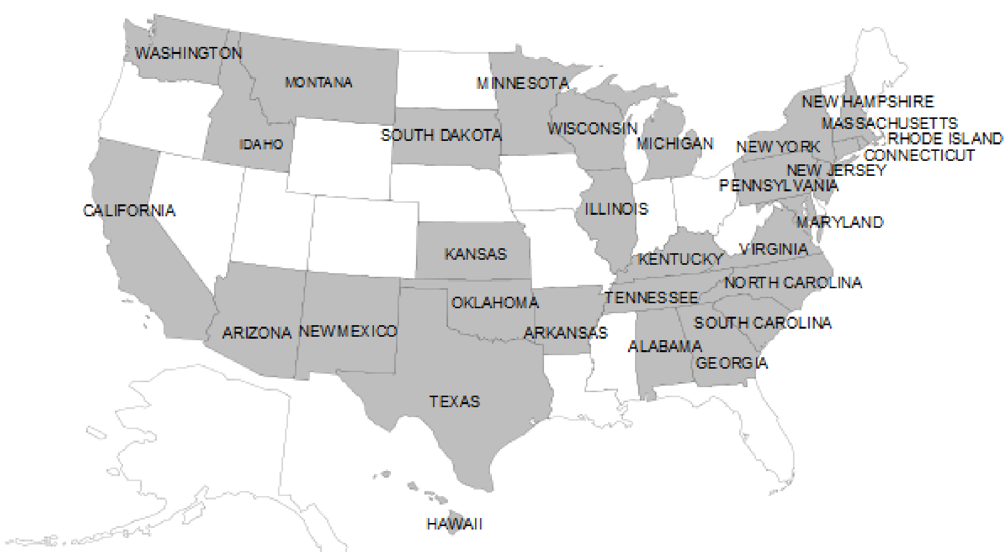

Figure 2.4: Map of responding states (*Aktan et al. 2003*)

For the last decade, the Ohio Department of Transportation (ODOT) has investigated the bridge deck cracking issues through an in-state field survey (*Crowl and Sutak 2002*), laboratory testing (*Delatte et al. 2007*), and a full-scale bridge deck study (*Delatte and Crowl 2012*). The survey covered a total of 116 HPC bridge decks constructed between 1994 and 2001. All 64 bridge decks that showed minimal or no cracking used coarse aggregate with higher absorption capacity (>1%). Meanwhile, 75% of the remaining 52 bridge decks with severe cracking used coarse aggregate with lower absorption capacity (<1%). To rule out other possible factors, a bridge deck was cast in 2002 in two phases in which the only difference between the two phases was coarse aggregate sources. Figure 2.5 shows that for Phase I the bridge deck above the green beams is in good condition. The arrow for Phase II shows the bridge deck above the green beams has evidence of cracking as seen by the transverse darkened/wet lines. Phase 2, which used lower absorption (<1%) coarse aggregate, cracked while Phase 1, which used higher absorption (>1%) coarse aggregate, did not show any cracking. This strongly suggested that the cracking resistance was related to the aggregate sources. In the later laboratory evaluation, they found that the internal curing by FLWA was able to reduce shrinkage in HPC, and a more significant reduction could be achieved by using larger coarse aggregate. These laboratory findings were also supported by a full-scale bridge deck field trail.

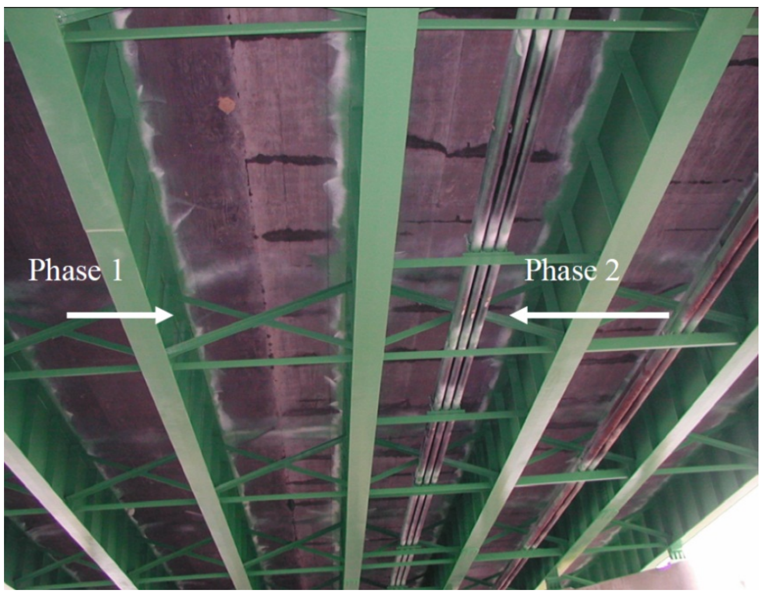

Figure 2.5: Phased construction of HPC bridge deck in Ohio. (*Delatte et al. 2007*)

2.9 SUMMARY

Table 2.4 gives a summary of the research highlights from each research. It can be seen that the drying shrinkage limit varies between different agencies. Virginia DOT has a series of limits for all the existing mixture designs currently used in the field. Those limits are specific to the mixture design used to develop them; consequently, the limits are not transferable between mixtures.

Table 2.4: Summary of shrinkage and cracking research by different agencies

Agency (Date)	Research Highlights
FHWA (*2012*)	**Shrinkage limit: 300 microstrain at 28 day; 500 microstrain long-term.**
UFGS*	**Shrinkage limit: 500 microstrain at 28day; For HVFA**:500 microstrain at 56 day.**
ASTM (2004)	Cracking potential classification (Table 2.1).
Texas DOT (2006)	Recommended concrete mixtures with low shrinkage, high tensile strength and low modulus of elasticity to control cracking. Many cracking mitigation methods were evaluated.
Virginia DOT (2003, 2010)	**Shrinkage limit: Table 2.3**.
Kansas DOT (2005)	Developed low cracking concrete mixture design (“KU Mix”).
New Jersey DOT (2008)	**Shrinkage limit: 450 microstrain at 56 day.**
West Virginia DOT (2013)	Developed cracking index to evaluate cracking risk.
Washington DOT (2010)	**Shrinkage limit: 320 microstrain at 28 day**
California DOT (2011)	Proposed drying shrinkage prediction model for concrete with SCMs and SRA (ALSN model).
Michigan DOT (2003)	Conducted survey pointing out that cracking performance related to restrained thermal and drying shrinkage.
Ohio DOT (2002, 2007, 2012)	Laboratory and field research recommended aggregate with higher (>1%) absorption capacity.

*UFGS – Unified Facilities Guide Specifications, for military service constructions;
**HVFA – High volume fly ash, minimum 50% class F fly ash.

In this literature review, recent studies on shrinkage and cracking issues on bridge decks were summarized. The current understanding of high-cracking-resistance concrete is that the concrete should have low free shrinkage, low early-age modulus of elasticity, and high tensile (or flexural) strength. From the testing perspective, several well-established tests exist for assessing shrinkage and/or cracking risk of concrete mixtures (e.g. standard/modified ring tests and scaled bridge deck). It is well-agreed upon that the restrained test (ring test) can provide the best prediction of concrete cracking. Along with materials properties tests (such as compressive strength, tensile strength and modulus of elasticity), it is possible to set shrinkage limits. It is anticipated that a laboratory testing procedure using the ring test and other mechanical properties tests is promising to determine cracking potential of HPC mixture for bridge decks.

3.0 EXPERIMENTAL

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, an ASTM C618 Class F fly ash, and an ASTM C1240 silica fume. Table 3.1 shows a summary of the oxide analysis of the cement and fly ash, both manufactured by Lafarge North America. Rheomac 100 silica fume, manufactured by BASF, contains nearly pure silica dioxide in noncrystalline form with approximately 1% crystalline silicate.

3.1.2 Admixtures

An ASTM C494 Type F polycarboxylate-based high-range water reducer (ADVA 190, and later ADVA Flex due to a change in product line) supplied by Grace Construction Products was used to achieve consistent workability (target 6 in slump). An air-entraining admixture supplied by Grace Construction Products was also added to achieve a target air content of 6% to ensure proper freeze/thaw resistance. One SRA (Eclipse 4500), which is compatible with the air entrainer, was used in some mixtures at a dosage rate of 2% of the total cementitious materials by mass.

3.1.3 Aggregates

The coarse and fine aggregate used in this study were from several different sources. Four siliceous aggregate sources were used. One was the local river gravel and river sand. Another two were sand and river gravel from the Bend area and the Medford area, respectively. Another was manufactured siliceous gravel and sand, known as Santosh aggregate, supplied by CalPortland. A limestone, commonly known as Spratt from Ontario, Canada, was also used. In addition, in some of the mixtures, a fine lightweight aggregate (FLWA) of expanded shale was used as a partial replacement of normal sand to provide an internal curing effect. Determination of the absorption capacity and desorption of the FLWA can be found in ODOT Report SPR711 (*Ideker and Fu 2013*). The properties of the aggregates are shown in Table 3.2.

Table 3.1: Cement and fly ash oxide analysis (wt %)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	MnO_2	P_2O_5	SrO	BaO	SO_3	Total Alkalies as Na_2O	Loss on Ignition
OPC	63.57	19.95	4.71	3.50	0.85	0.25	0.27	0.24	0.09	0.09	0.16	0.06	3.19	0.43	3.19
Fly Ash	10.20	55.24	15.77	6.27	3.64	3.64	2.08	0.94	0.12	0.23	0.32	0.62	0.70	-	0.23

Table 3.2: Aggregates properties (as received)

	Specific Gravity	Absorption Capacity (%)	Desorption Capacity (%)	Fineness Modulus
Local sand	2.41	3.08	-	3.0
Local gravel (3/4" MSA)	2.44	2.58	-	7.1
Bend sand	2.54	2.58	-	2.9
End gravel (3/4" MSA)	2.59	2.27	-	7.5
Medford sand	2.48	3.46	-	2.6
Medford gravel (3/4" MSA)	2.53	3.17	-	7.2
Santosh sand	2.58	2.74	-	3.3
Santosh gravel (1" MSA)	2.62	2.04	-	6.7
Limestone (Ontario, Canada)	2.68	0.58	-	6.5
Expanded shale	1.55	17.50	16.0	2.7

3.2 METHODS

3.2.1 Fresh Properties

Fresh properties of all freshly mixed concrete were taken as a quality control measure. Fresh properties consisted of slump, air content, unit weight, and temperature. As previously mentioned, the target slump was 150 mm (6 in, 5.5 ± 2.5 in. by ODOT specification), and the target air content was 6% (6 ±1.5 % by ODOT specification). A pressure air meter was used for concrete without lightweight aggregate (pressure method, ASTM C231), and a roll-a-meter was used for concrete with FLWA (volumetric method, ASTM C173). Fresh concrete temperature was measured at the end of each mixing using an infrared thermometer.

3.2.2 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 75mm × 75mm × 285mm (3 × 3 × 11.25 in). The specimens were removed from the mold 24 hours after casting. Then the specimens were stored in a moist room of 23 ± 2 °C (73.5 ± 3.5 °F) and >95% RH for the desired curing duration (i.e. 3 days or 14 days in this study). Upon the end of curing duration, the specimens were moved to an environmental chamber with control drying condition of 23 ± 2 °C and 50 ± 4 % RH. During drying, the length was monitored by a comparator. The mass change was also recorded.

3.2.3 Restrained Shrinkage Test

Over the last few decades, the shrinkage ring test has been frequently used as a testing technique to identify potential cracking risks of certain concrete and mortar mixtures. There are two standard testing procedures based on similar principles (as shown in Figure 3.1): ASTM C1581-2009 (*ASTM C1581 2009*) and AASHTO T334-08 (*AASHTO T334-08 2008*). The major difference is the concrete thickness. The thickness of the concrete ring specimen for ASTM C1581 is 1.5 in, and the thickness for the AASHTO T334 ring is 3 in. Detailed dimensions of these two types of rings are shown in Figure 3.1.

Compared to the standard testing procedure, modifications were applied in this project: 1) to achieve more accurate cracking evaluation, three rings instead of two were tested for each mixture; 2) specific curing durations (3 and 14 days) were used to simulate field curing conditions; and 3) mechanical properties at 28-day age were tested on match cured cylinders.

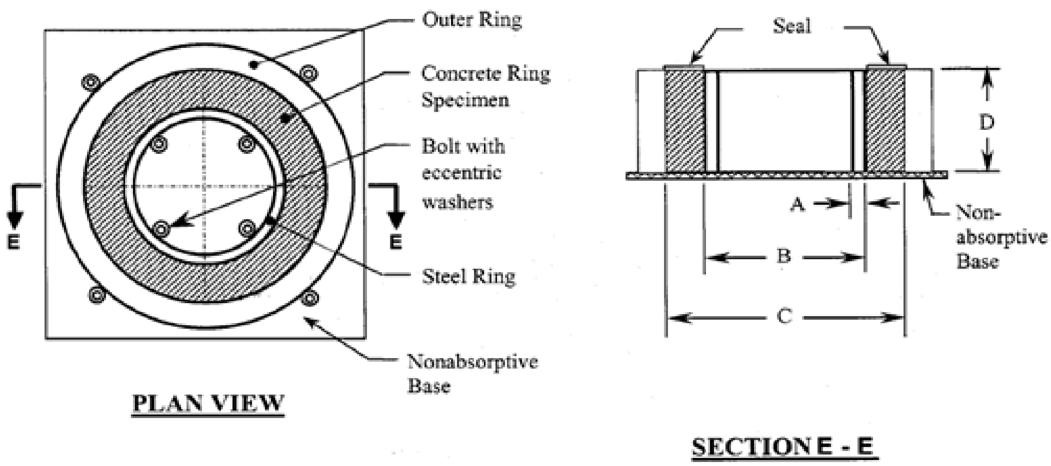

Figure Dimensions	ASTM	AASHTO
A	12.5 ± 0.13 mm	13 ± 0.4 mm
B	330 ± 3 mm	324 ± 5 mm
C	406 ± 3 mm	476 ± 5 mm
D	150 ± 6 mm	152 ± 5 mm

Figure 3.1: Dimension of rings test setup

A sample of freshly mixed concrete was compacted in a circular mold around an instrumented steel ring. The compressive strain developed in the steel ring caused by the restrained shrinkage of the specimen 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 (73.5 ± 3.5 °F). The outer ring was removed at 24 h and the moist curing continued. During the curing process, the burlap was re-wetted as necessary to maintain a 100% RH under the polyethylene film. At the end of the curing process, the burlap was removed and the top surface of the specimen was sealed with a silicone sealant to allow for drying only in the horizontal (radial) 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.

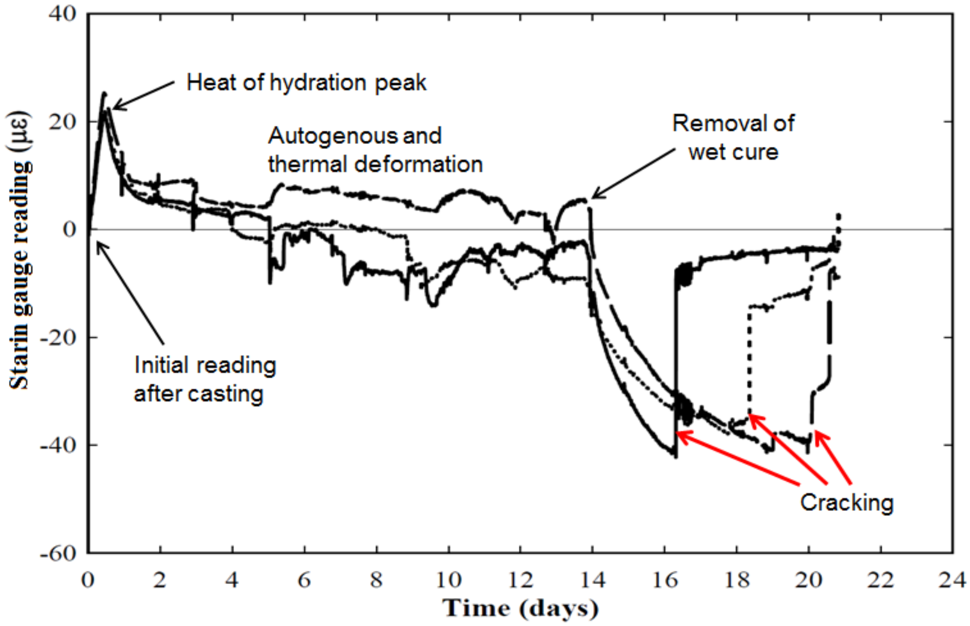

Figure 3.2: A typical averaged strain gauge reading in ring tests (3 replicates)

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 tensile strain due to expansion caused by the heat released from hydration of the cement paste in concrete. Then after the removal of the outer rings, the concrete ring specimens were cured by wetted burlap until the end of the desired curing duration. During this period, some of the tensile strain in the steel ring was offset by the compressive strain generated due to autogenous shrinkage. Some noise in the strain gauge reading was also recorded during this period, which was believed to be due to the temperature variation. At the time of burlap removal, the compressive strain due to drying immediately dominated. At the end of the test, 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 could also be calculated as per ASTM C1581, and then used as another parameter in cracking evaluation. A detailed stress rate analysis and calculation could be found in literature (*See et al. 2004*). More information about the qualitative analysis of the restrained ring test can be found in the ACI Committee 231 report on early-age cracking (ACI Committee 231 2010).

3.2.4 Mechanical Properties Test and Curing Conditions

The mechanical properties were tested for each mixture at 28-day age, including compressive strength (ASTM C39), splitting tensile strength (ASTM C496), and modulus of elasticity (ASTM C469). For each mixture, $\phi 100 \times 200$ mm ($\phi 4 \times 8$ in) cylindrical samples were cured in two conditions: standard 28-day wet cure, and 28-day match cured. For standard curing, samples were demolded 24 hours after casting and stored in a standard moisture room until testing. For match curing, samples were demolded 24 hours after casting and stored in the standard moisture room until the end of the desired wet curing periods. Then these samples were moved to the drying chamber and stored near the ring specimens until testing. This was to ensure that the measured mechanical properties were representative of ring specimens. For instance, if the curing duration of the rings was 3 days, then for the match cured condition, the cylinders tested at 28-day age (from casting) went through 24 hours in the mold, 2 days in the moist room, then 25 days in the drying chamber. Because the 28-day properties are predominantly used in industrial practice, the 28-day compressive strength, tensile strength, and modulus of elasticity were the main parameters used in this research, regardless of the curing history of the samples.

3.2.5 Summary

This project is centered on establishing a link between standard mechanical property testing, drying shrinkage and the restrained ring tests of concrete specimens. For each mixture, the following tests were performed:

- 6 Cylinders for compressive strength (3 replicates), splitting tensile (3 replicates), and static modulus of elasticity (2 replicates) for 28-day wet cured condition;

- 6 Cylinders for compressive strength (3 replicates), splitting tensile (3 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;

- 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.

3.3 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 34.5 MPa (5000 psi) with minimum strength of 27.6 MPa (4000 psi). A w/cm of 0.37 was used in most of the mixtures, except for an ordinary portland cement (no SCMs) where a w/cm of 0.42 was used. The total cementitious materials content was 375 kg/m^3 (663 lb/yd^3), containing 30% class F fly ash and 4% silica fume as mass replacement. The coarse and fine aggregate content were 1071 kg/m^3 (1810 lb/yd^3),and 659 kg/m^3 (1810 lb/yd^3),respectively for local materials. The high range water reducer and air entrainer dosages were adjusted to achieve similar workability and air content for all mixtures. This mixture design was applied as a baseline with necessary modifications. When doing the mixture modifications, one principle was to keep all materials the same as the base line in terms of volume. This was achieved because the specific gravity of all the materials was known. In addition, a proprietary mortar mixture was used. Table 3.3shows the detailed mixture proportioning.

Table 3.3: Concrete mixture proportioning

Mixture	Cement (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Sand (kg/m^3)	FLWA (kg/m^3)	SRA (kg/m^3)
HPC	249	112	15	139	1071	659	-	-
SRA	249	112	15	131	1071	659	-	7.5
FLWA	249	112	15	139	1071	400	164	-
SYN	249	112	15	131	1071	400	164	7.5
OPCA	375	-	-	139	1071	659	-	-
OPCB	375	-	-	158	1071	659	-	-
LS	249	112	15	139	1100	740	-	-
BD	249	112	15	139	1140	695	-	-
MD	249	112	15	139	1114	678	-	-
ST	249	112	15	139	1153	705	-	-
RM	Proprietary mortar material, mixing according to manufacturer's instruction							

The HPC, SRA, FLWA, SYN, OPCA, OPCB uses local gravel and river. The LS, BD, MD, ST, and RM represent mixtures using different aggregate sources. A detailed description of all mixtures evaluated by ring tests is given in Table 3.4. The SYN (short for synergy) mixtures contained FLWA and SRA. The FLWA in SYN1 was "pre-wetted", meaning the moisture content was brought up to about 20%, which was more than the absorption capacity (about 18%). The FLWA in SYN2 was "pre-soaked", meaning the FLWA was soaked with all mixing water for over 48 hours. In this case, the moisture content of the normal coarse and fine aggregate were measured in advance in order to calculate the exact amount of mixing water needed. The FLWA in SYN3 was "SRA solution soaked", meaning the FLWA was soaked with all mixing water with SRA in it for over 48 hours. Similar to SYN2, the moisture content of the normal coarse and fine aggregate were measured in advance, and then the SRA solution was prepared before soaking. The concentration of SRA solution was close to the mixing water plus SRA in SYN2. The difference between SYN3 and SYN2 was that the SRA was present only in the mixing water in SYN2 while the SRA was present mostly within the pores of FLWA as pre-soaked "water". The purpose was to determine whether there was a synergy between the SRA and LWFA.

Table 3.4: Mixtures for ring tests

Ring Type	Mixture ID	Coarse aggregate type	Fine aggregate type	w/cm	Wet curing duration (days)	Other descriptions
ASTM	HPC1	Local	Local	0.37	3	Control HPC
	HPC2	Local	Local	0.37	14	Control HPC
	SRA1	Local	Local	0.37	3	2% SRA
	SRA2	Local	Local	0.37	14	2% SRA
	FLWA1	Local	Local + FLWA	0.37	3	25% expanded shale
	FLWA2	Local	Local+ FLWA	0.37	14	25% expanded shale
	SYN1	Local	Local	0.37	14	2% SRA + 25% expanded shale (pre-wetted)
	SYN2	Local	Local	0.37	14	2% SRA + 25% expanded shale (water soaked)
	SYN3	Local	Local	0.42	14	2% SRA + 25% expanded shale (SRA solution soaked)
	OPCA	Local	Local	0.37	14	No SMCs
	OPCB	Local	Local	0.42	14	No SCMs, higher w/cm
	BD	Bend, OR	Bend, OR	0.37	14	BD = Bend
	MD	Medford, OR	Medford, OR	0.42	14	MD = Medford
	LS	Limestone	Local	0.37	14	LS = Limestone
	ST1	Santosh	Santosh	0.37	3	Sieved coarse aggregate (MSA ¾”) ST = Santosh
	RM	-	-	-	3	RM = repair mortar
AASHTO	HPC3	Local	Local	0.37	3	Control HPC
	HPC4	Local	Local	0.37	14	Control HPC
	SRA3	Local	Local	0.37	3	2% SRA
	FLWA3	Local	Local + FLWA	0.37	3	25% expanded shale
	ST2	Santosh	Santosh	0.37	3	Santosh as received (Coarse aggregate MSA 1”)

4.0 RESULTS AND DISCUSSION

4.1 FRESH PROPERTIES

Table 4.1 shows the summary of fresh properties for all the mixes. When the slump was more than 3 in, there was no particular effort needed to compact concrete in the mold. For ASTM rings, the vibration table was consistently used for all mixes to achieve good compaction.

Table 4.1: Fresh Properties

Ring Type	Mixture ID	Slump (in)	Air content (%)	Unit Weight (lb/ft^3)	Temperature (°C)
ASTM	HPC1	5	6.0	144.1	21.4
ASTM	HPC2	5	4.5	146.5	23.0
	SRA1	9	5.5	141.4	21.6
	SRA2	5 ½	4.5	145.4	20.8
	FLWA1	8 ½	7.5	138.4	20.4
	FLWA2	8	3.0	143.9	22.0
	SYN1	6	6.0	136.4	20.0
	SYN2	5	2.5	144.3	24.8
	SYN3	2 ½	2.5	142.8	19.2
	OPCA	8	3.0	151.1	23.8
	OPCB	2 ¼	3.5	148.4	25.4
	LS	3 ¼	7.0	138.3	19.8
	MD	2	5.0	142.9	23.0
	BD	3 ¾	7.0	141.9	25.4
	ST1	3 ¾	5.5	144.0	22.8
	RM	-	-	-	25.0
AASHTO	HPC3	3 ¾	6.0	142.8	19.0
	HPC4	4	4.5	145.3	19.8
	SRA3	3 ½	4.0	146.2	20.8
	FLWA3	3 ¼	7.5	135.6	22.6
	ST2	8 ¼	7.5	137.3	19.6

4.2 MECHANICAL PROPERTIES

Table 4.2 shows the summary of compressive strength, splitting tensile strength, and modulus of elasticity of all mixtures. Most of the mixtures met the 34.5 MPa (5000 psi) strength target (27.6 MPa, 4000 psi minimum strength). For curing, in addition to the standard 28-day wet cure method, cylinder samples were also match cured with ring specimens to match the exact curing duration. For instance, cylinders using the 28-day match cured condition were wet cured for 3 days (the first 24 hours in the mold) and exposed to the drying environment for 25 days before testing.

One observation from Table 4.2 was the compressive and tensile strengths of the 14-day match cured cylinders were consistently higher than the strengths of the 28-day wet cured cylinders (except for SYN series). Note that match cured cylinders went through significant drying duration (14 days), which is considered unfavorable for strength gain for concrete by classic theories. The reason for the strength difference in the current work is unknown.

To statistically explore the strength difference between the two curing conditions, a HPC control mixture was cast consisting of 60 cylinders. Thirty of the cylinders went through 28-day standard wet curing, while the remaining cylinders went through 14-day wet cure followed by 14-day standard drying. Only the 28-day age mechanical properties were tested. For each property, 10 samples were tested, and their average and standard deviation were calculated. The averages, standard deviations, and p-values from the t-Test (paired two samples for means) are shown in Table 4.3. All p-values were less than 0.05, so the differences in mechanical properties due to curing condition were statistically significant.

Table 4.2: Concrete Mechanical Properties

Ring Type	Mixture	Wet Curing Duration for Rings Prisms (days)	28-Day, Wet Cured for Cyilnders				28-Day, Match Cured for Cylinders		
			Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)		Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
ASTM	HPC1	3	28.8	3.42	22.9		30.3	3.49	24.4
	HPC2	14	35.4	4.06	28.7		39.9	4.4	27.5
	SRA1	3	33.2	3.97	28		-	-	-
	SRA2	14	36.4	3.78	29.3		39.1	4.08	27.4
	FLWA1	3	36.6	3.72	24.2		-	-	-
	FLWA2	14	45.4	5.17	29.6		53.5	5.48	29.7
	SYN1	14	26.1	2.76	22		24.2	2.93	21.1
	SYN2	14	43.5	4.05	27.2		40.3	4.02	28.2
	SYN3	14	38.3	3.71	27		34	4.39	26.4
	OPCA	14	44.7	3.67	32.2		45.7	4.29	33.1
	OPCB	14	34.5	3.42	30		-	-	-
	LS	14	34.2	3.9	32.4		35.9	4.12	25.6
	BD	14	24.5	2.68	31.2		27.5	3.27	27.2
	MD	14	27.1	2.91	32		30.7	3.33	28.4
	ST1	3	34.6	3.92	31.1		31.4	3.7	26.8
	RM	3	-	-	-		61.2	5.86	29.4
AASHTO	HPC3	3	29	3.58	32.3		27	2.98	27.2
	HPC4	14	39.7	3.99	35.5		42.1	4.18	29.8
	SRA3	3	38.1	3.67	32.3		33.9	3.55	30.2
	FLWA3	3	36.3	3.76	28.5		31.3	3.16	25.2
	ST2	3	27.8	3.25	29.7		23.2	2.15	25.6

Table 4.3: Statistical study of curing conditions

Batch A*		**Compressive Strength (MPa)**			**Splitting Tensile Strength (MPa)**			**Modulus of Elasticity (GPa)**	
Curing condition		28 day wet cure	14 wet + 14 dry		28 day wet cure	14 wet + 14 dry		28 day wet cure	14 wet + 14 dry
Average of 10 individual tests		18.1	21.0		2.29	2.94		23.4	19.2
Std. Dev.		2.03	2.29		0.22	0.13		2.34	1.34
P-value		0.015992			0.000008			0.000136	
Batch B**		**Compressive Strength (MPa)**			**Splitting Tensile Strength (MPa)**			**Modulus of Elasticity (GPa)**	
Curing condition		28 day wet cure	14 wet + 14 dry		28 day wet cure	14 wet + 14 dry		28 day wet cure	14 wet + 14 dry
Average of 10 individual tests		25.7	26.0		2.82	3.13		26.5	22.5
Std. Dev.		2.27	1.39		0.33	0.27		1.40	1.37
P-value		0.390923			0.032711			0.000183	

*Fresh properties: 7.75% air content, 5 ¼” slump, 21.4 ºC, 134.4 lb/ft^3 unit weight.
**Fresh properties: 6.5% air content, 5” slump, 23.0 ºC, 141.0 lb/ft^3 unit weight.

4.3 FREE SHRINKAGE

Table 4.4 gives a summary of free shrinkage measurements of all mixtures at different ages up to 180 days. In the first part of the table, HPC2 represents the control mixture for all free shrinkage tests and accompanying the ASTM ring tests. The percentage in the brackets show the relative scale of certain shrinkage compared to HPC2 at the same age. In the second half of the table, all mixtures are referenced to HPC3, which was the control mixture for AASHTO ring tests.

Table 4.4: Summary of free shrinkage (microstrain) and relative free shrinkage (%) to HPC

Mixture	Curing Duration (days)	7 day	28 day	56 day	90 day	180 day
HPC1	3	340(117)	600(109)	727(115)	780(109)	863(113)
HPC2*	**14**	**290(100)**	**550(100)**	**630(100)**	**715(100)**	**760(100)**
SRA1	3	133(45)	337(61)	443(70)	497(69)	-
SRA2	14	190(65)	447(81)	573(90)	640(89)	710(93)
FLWA1	3	280(96)	535(97)	633(100)	703(98)	-
FLWA2	14	323(111)	663(120)	800(126)	870(121)	917(120)
SYN1	14	140(48)	345(62)	465(73)	530(74)	620(81)
SYN2	14	120(41)	287(52)	400(63)	507(70)	-
SYN3	14	107(36)	287(52)	417(66)	477(66)	570(75)
OPCA	14	360(124)	600(109)	690(109)	750(104)	830(109)
OPCB	14	300(103)	557(101)	677(107)	747(104)	837(110)
LS	14	240(82)	380(69)	430(68)	457(63)	563(74)
BD	14	473(163)	860(156)	960(152)	1033(144)	1167(154)
MD	14	317(109)	610(110)	730(115)	810(113)	897(118)
ST1	3	277(95)	500(90)	527(83)	617(86)	-
RM	3	207(71)	447(81)	610(96)	740(103)	853(112)
HPC3	**3**	**347(100)**	**623(100)**	**720(100)**	**760(100)**	**837(100)**
HPC4	14	313(90)	550(88)	663(92)	773(102)	804(96)
SRA3	3	160(46)	383(61)	490(68)	543(71)	617(74)
FLWA3	3	313((90)	577(93)	710(99)	757(100)	807(96)
ST2	3	277(80)	540(87)	630(87)	640(84)	697(83)

*HPC2 is the average of two samples because the third sample was an outliner based on the COV for ASTM C 157. This resulted in an unusually high shrinkage of 980 microstrain at 28 day and 1360 microstrain at 180 day. Furthermore since the research team has conducted many of this standard "control" mixture with a 14-day wet cure it was clear from comparison to other mixtures, such as HPC4 and mixtures from a previous ODOT project, SPR 711, that this one bar was clearly an outlier.

The free shrinkage at the early age was effectively reduced for mixtures using mitigation methods (SRA, FLWA, or synergy of both). However, given the high shrinkage nature of this HPC mixture, using the FLWA alone was not as effective as the other two methods, especially at later ages. The synergy of SRA and FLWA most significantly reduced the free shrinkage. In addition, different aggregate sources had a great impact on the shrinkage. By using limestone aggregate, the shrinkage was significantly reduced compared to all siliceous aggregate mixture designs. More discussion is given in the following section. All individual shrinkage development curves are in Appendix A.

4.3.1 Shrinkage Mitigation Methods

Figure 4.1 and Figure 4.2 show the shrinkage development curves of different mitigation methods under 3-day and 14-day wet cure conditions.

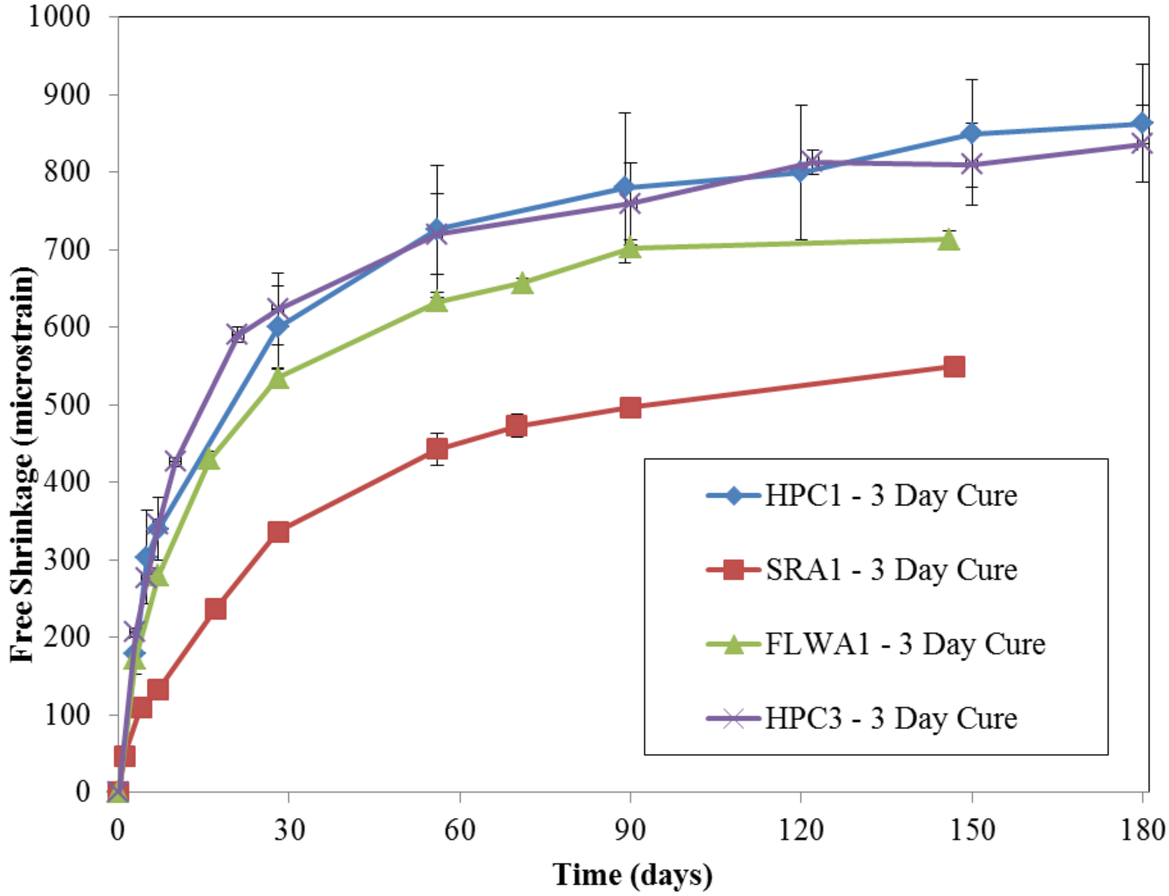

Figure 4.1: Free shrinkage versus drying time, 3-day cure, effect of shrinkage mitigation methods

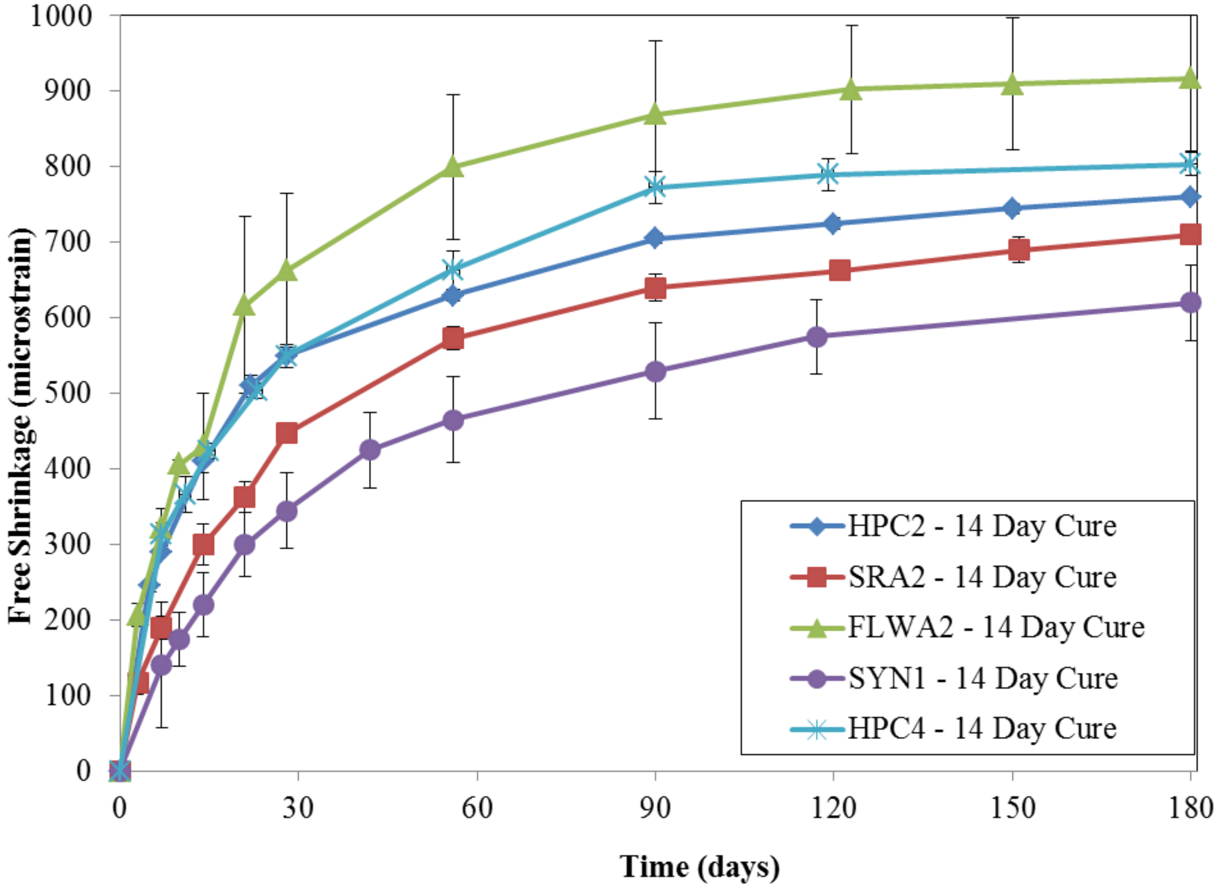

Figure 4.2: Free shrinkage versus drying time,14-day cure, effect of shrinkage mitigation methods

By incorporating SRA in the HPC mixture, the shrinkage was significantly reduced for both 3-day wet cured samples and 14-day wet cured samples. For FLWA mixtures, FLWA helped in reducing shrinkage for 3-day cured samples but had little effect on the 14-day cured samples. The synergy of SRA and FLWA was the most effective method in reducing drying shrinkage. These findings were consistent with the findings reported in SPR711 report (*Ideker and Fu 2013*).

4.3.2 Aggregates

As discussed previously, aggregate type also has significant impact on shrinkage behavior. As shown in Figure 4.3, all natural siliceous aggregate (mixes HPC2, BD and MD) resulted in high shrinkage both at early age and long term. It should be noted that the BD and MD mixtures did not represent the mixture design used in the field. This was because the mixture design for these two aggregates was simply converted from the control HPC mixture by keeping all components equal in volume. The ST1 mixture, which used manufactured siliceous aggregates, also performed better than the control mix. Another interesting observation was the application of limestone coarse aggregate. By using limestone instead of siliceous river gravel as coarse aggregate, free shrinkage was reduced by 45% at 28 days after drying compared to the control HPC mixture. The RM, as a mortar mix, showed good shrinkage performance, likely due to the high volume of quartz sand in the aggregate, which is believed to perform best among aggregates from a shrinkage point of view(*Troxell and Davis 1956, Burrows 1998*). Nevertheless, the long term shrinkage (> 800 microstrain at 180 day) was still considered high likely due to thigh paste content in the mixtures.

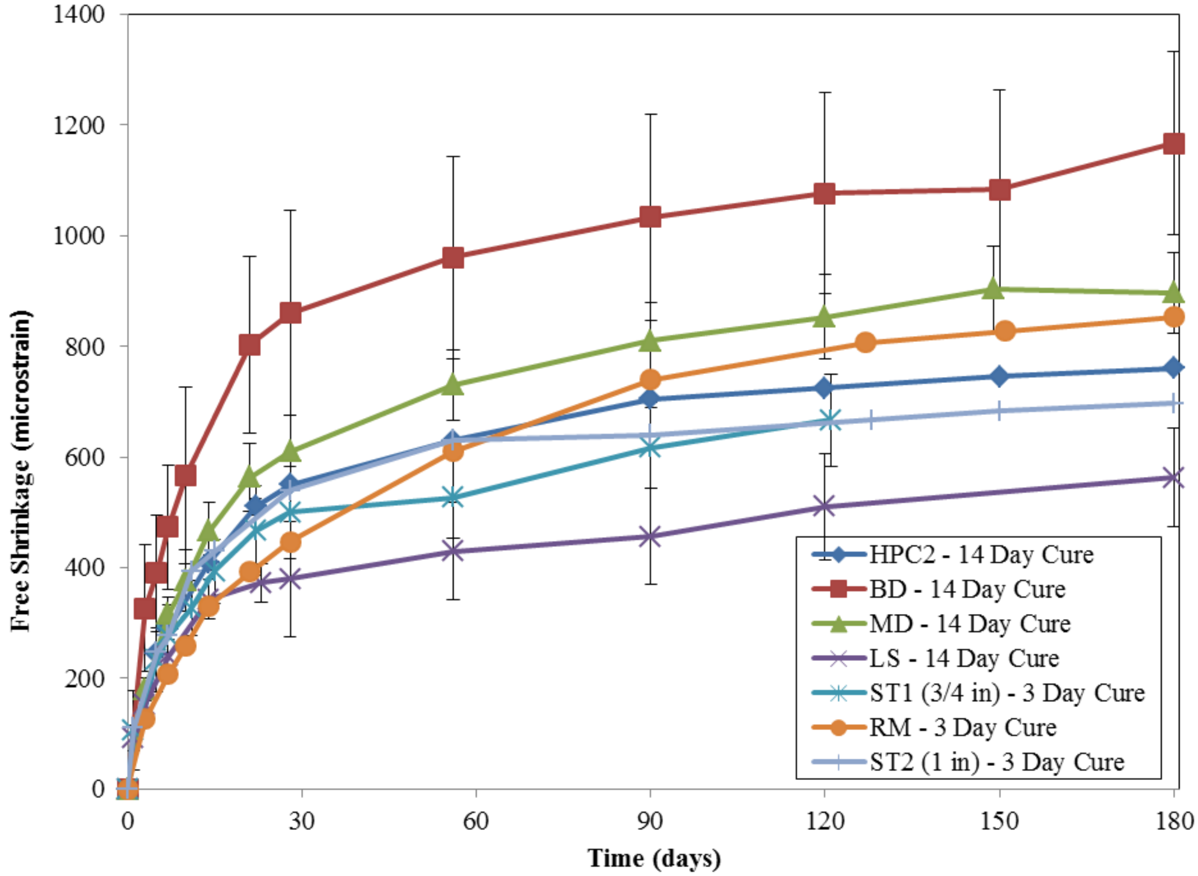

Figure 4.3: Free shrinkage versus drying time, 14 day cure, effect of aggregates

Given a closer look at the physical properties of different aggregates, it seems that the absorption capacity could affect the shrinkage performance. Among HPC2, BD, MD, LS, and ST1, limestone (aggregate in mixture LS) had the lowest absorption capacity (0.58 %), followed by Santosh (aggregate in mixture ST, 2.04 % for rock and 2.74% for sand), Bend (aggregate in mixture BD, 2.27 % for rock and 2.58 % for sand), local (HPC, 2.58 % for rock and 3.08 % for sand), and, Medford (aggregate in mixture MD, 3.17 % for rock and 3.46 % for sand). This correlates well with the shrinkage values (LS < ST < BD < HPC < MD). Generally, the absorption capacity correlates to the modulus of elasticity of the aggregate (*Carlson 1938, Alexander 1996, Deshpande et al. 2007*). The lower the absorption capacity indicates fewer pores in the aggregate particles and therefore likely a higher modulus of elasticity. Higher modulus of elasticity could better resist volume change when the cement paste shrinks due to drying. However, no conclusion could be drawn due to many other possible variations such as aggregate gradation, sand equivalency, shape, and possibly aggregate mineralogy. Therefore, the authors believe the effect of the aggregate on drying shrinkage and cracking merits further investigation.

4.3.3 SCMs and W/CM

To investigate the impact of w/cm and SCMs on shrinkage two mixtures were modified from the HPC standard mixture design. OPCA and OPCB are full portland cement mixtures with no SCM replacement (see Table 3.4 for details). Additionally the w/cm was modified for OPCB to be 0.42. Figure 4.4 shows the effect of water-to–cementitious material ratio as well as incorporation of SCMs as compared to the control HPC mixture. Both OPCA (w/cm = 0.37) and OPCB (w/cm = 0.42) both showed over 800 microstrain shrinkage at 180 days of age, which is considered high shrinkage. Comparing OPCA and OPCB to HPC2 and HPC4 (the presence of SCMs (30% fly ash and 4% silica fume) did not contribute to the high shrinkage of the HPC control mixtures. For OPC mixtures, when changing the w/cm from 0.37 (OPCA) to 0.42 (OPCB), the impact on shrinkage was insignificant. OPCA showed higher early age shrinkage than OPCB, and the long term (180 days) shrinkage of OPCA and OPCB were similar.

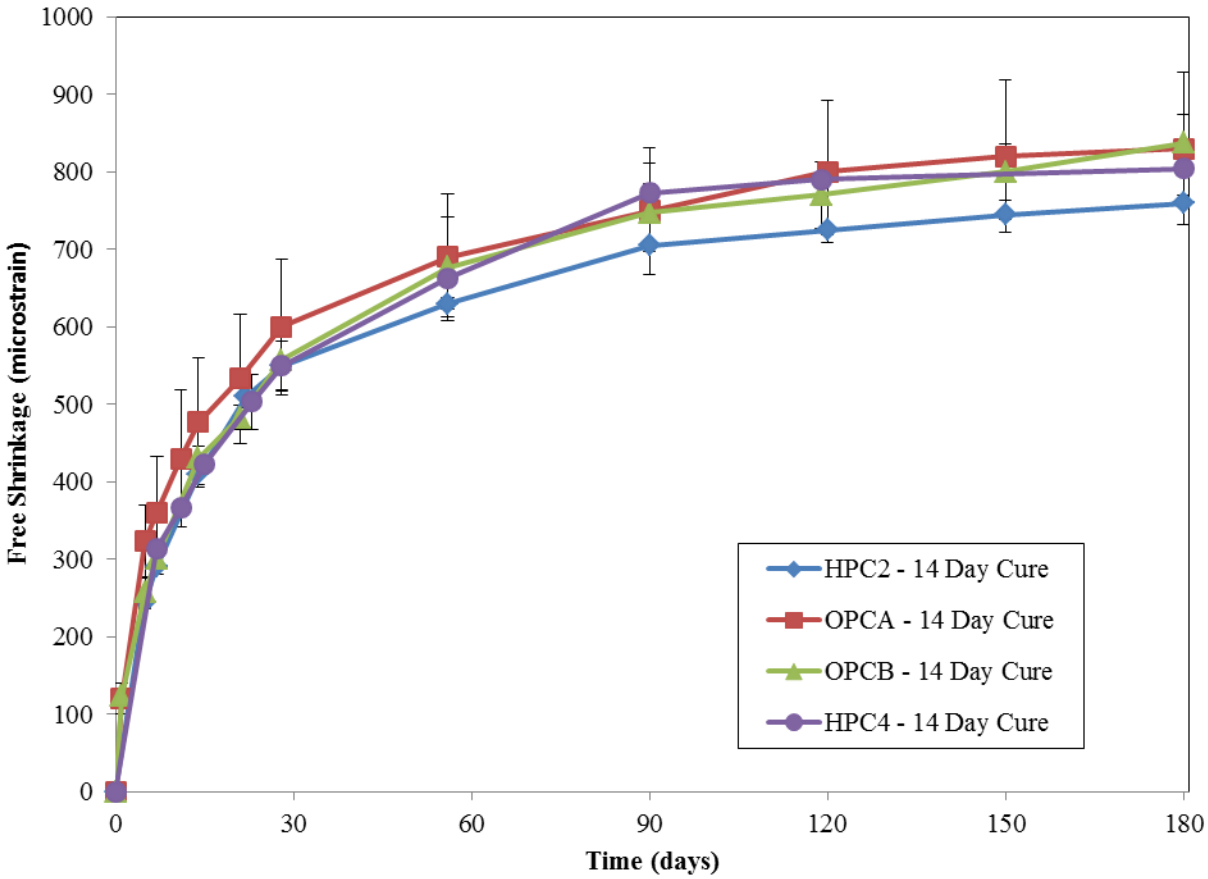

Figure 4.4: Free shrinkage versus drying time, 14-day cure, effect of w/cm and SCMs

4.3.4 Precondition of SYN Series

Figure 4.5 shows the shrinkage of SYN1, SYN2, and SYN3. It shows the combination of SRA and FLWA reduced the drying shrinkage by about 50%. Note that the FLWA in SYN1 was pre-wetted, which was accomplished by bringing the moisture content of the FLWA to about 20%, and SRA was added during mixing. The FLWA in SYN2 was completely soaked under water for 48 hours before mixing, and SRA was added during mixing. FLWA in SYN3 was soaked under SRA solution for 48 hours before mixing. Different conditioning of the FLWA had insignificant effect on drying shrinkage. The SYN3 with SRA solution soaked FLWA showed the lowest shrinkage among all three SYN mixtures, possibly due to a delayed release of SRA stored in the pores of FLWA.

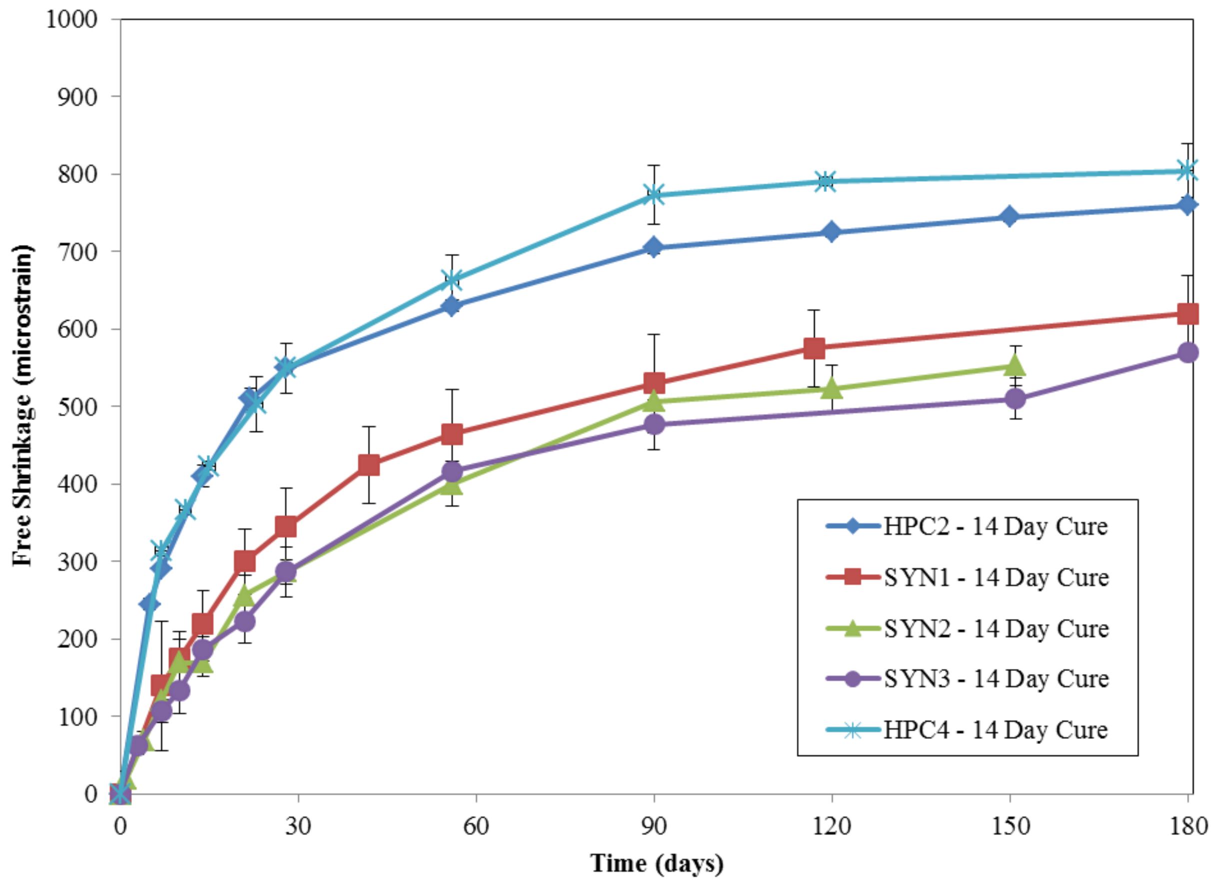

Figure 4.5: Free shrinkage versus drying time, 14-day cure, effect of FLWA precondition in SYN

4.4 RESTRAINED SHRINKAGE TEST

4.4.1 ASTM C1581

Table 4.5 gives 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 gauge, 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. 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 issues. On the other hand, time-to-cracking is involved in the stress rate calculation. In other words, stress rate provides a more comprehensive evaluation.

Figure 4.6 shows a good relationship of time-to-cracking with stress rate, with a correlation coefficient of over 0.89. The power-law relationship indicates that with the decrease of stress rate, the time-to-cracking would be significantly prolonged.

Table 4.5: Summary of time-to-cracking and stress rate of ASTM ring tests

Mixture	Curing Duration (days)	Time-to-Cracking, Days				Stress Rate, MPa/Day				Cracking Potential Classification*
		A	B	C	Ave.	A	B	C	Ave.	
HPC1	3	4.0	5.5	5.2	4.9	0.380	0.315	0.338	0.344	H
HPC2	14	4.4	4.6	3.6	4.2	0.343	0.281	0.482	0.369	H
SRA1	3	13.9	18.4	18.8	17.0	0.094	0.073	0.094	0.087	L
SRA2	14	16.1	14.9	11.6	14.2	0.104	0.093	0.139	0.112	ML
FLWA1	3	6.5	7.0	7.3	6.9	0.238	0.213	0.284	0.245	MH
FLWA2	14	7.4	7.9	n/a	7.7	0.245	0.263	n/a	0.254	MH
SYN1	14	19.7	14.0	14.0	15.9	0.115	0.070	0.060	0.081	L
SYN2	14	15.1	21.1	14.7	17.0	0.117	0.082	0.114	0.105	ML
SYN3	14	11.3	17.3	11.2	13.3	0.106	0.111	0.115	0.111	ML
OPCA	14	4.0	5.6	5.3	5.0	0.340	0.275	0.329	0.315	MH
OPCB	14	4.2	4.6	3.6	4.1	0.257	0.266	0.238	0.254	MH
LS	14	40.9	no crack at 60 day	23.1	>41	0.045	≈0.10	0.099	0.082	L
BD	14	3.5	7.1	8.4	6.3	0.410	0.305	0.197	0.304	MH
MD	14	6.3	4.0	1.9	4.1	0.279	0.208	0.283	0.257	MH
ST1	3	11.2	8.4	11.4	10.3	0.205	0.243	0.227	0.225	MH
RM	3	28.0	33.0	23.0	28.0	0.072	0.063	0.084	0.073	L

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

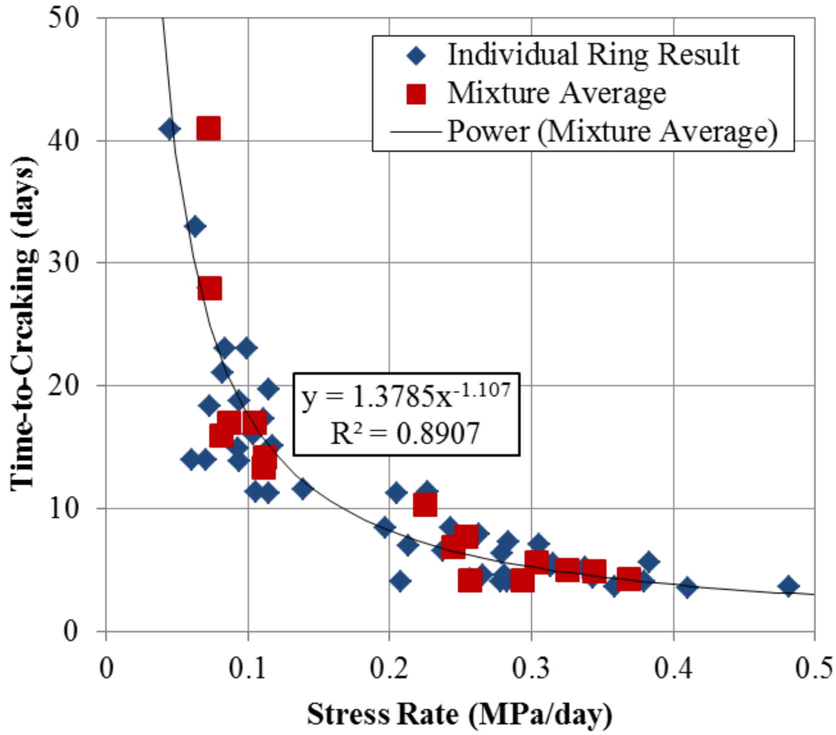

Figure 4.6: Time-to-cracking versus Stress rate

It is noted that SRA significantly prolonged the time-to-cracking (ToC), and decreased the stress rate. Comparing HPC to SRA, the ToC was prolonged from around 5 days to more than 14 days, which lowered the cracking risk from "high" to "moderate low" or even "low". FLWA also prolonged the ToC and decreased the stress rate, but not as effectively as SRA. SYN showed the lowest free shrinkage (Table 4.4) and a similar ToC to that of SRA. From the ring results, different conditioning of the FLWA did not make a significant difference in cracking performance. SYN1 and SNY2 both cracked around 14 to 20 days, which means the pre-wetted FLWA condition and the pre-soaked FLWA condition would not make a significant difference. It was interesting to see that the SRA solution-soaked FLWA (SYN3) was less effective than SYN1 and SYN2 where the SRA was added during mixing. Consequently, if SRA and FLWA are used together in construction projects, the most effective way is to use pre-wetted or pre-soaked (as in the field under sprinkler systems) FLWA and then add SRA while mixing.

By comparing OPCA and OPCB to the control HPC mixtures, they showed similar cracking resistance and high cracking risk. This means for the given mixture design and locally available siliceous aggregate, the incorporation of SCMs and variation of w/cm between 0.37 and 0.42 did not significantly affect (either improve or aggravate) cracking performance.

Aggregates sources resulted in significant effects in cracking performance, much more than previously believed. By simply switching from the local siliceous aggregate to a limestone, the shrinkage cracking performance was significantly improved. Among all mixtures, mixture LS, which was a limestone HPC, lasted the longest before cracking. Mixture LS resulted in an average ToC of 41 days comparing to about 5 days ToC for the control HPC mixtures. Similarly, the manufactured Santosh aggregate (ST) also outperformed the local aggregate, extending the ToC to about 10 days. This might well relate to the interfacial transition zone (ITZ) theory. Limestone might contribute to an improved IZT via chemical bonding as hydration products precipitate on the limestone surfaces in preference to that of siliceous ones. In addition, due to the fact that the limestone and manufactured aggregates were angular in shape and rough in surface, more bonding surface and better mechanical bonding formed in the ITZ could help to improve the cracking resistance.

Another possible reason behind why the limestone mixture lasted for such a long time is the stress relaxation. In fact one LS ring specimen showed no crack at 60 days after initiation of drying, when the test was terminated. One set of strain gauge data is presented in Figure 4.7, showing the strain development in three individual ring specimens of mixture LS.

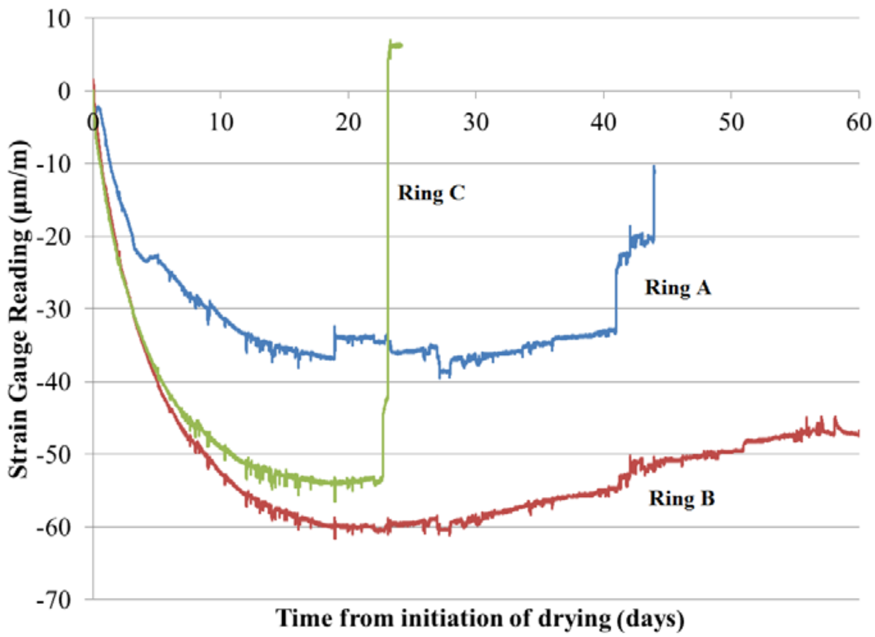

Figure 4.7: Strain development versus time, three individual rings of mixture LS

Ring C showed a typical response as most tests, which consisted of an increase in strain and a “sharp jump” toward zero strain at the end. However, ring B did not show this sudden change, but rather a slow decrease in strain indicating stress relaxation in the ring. This can be seen in the later age of ring A as well. After a certain period of time, about 28 days in this case, the effect of stress relaxation started to impact the cracking behavior of the ASTM ring specimens. In other words, if a concrete mixture survived 28 days or longer in the ASTM ring, the cracking potential could be further lowered due to stress relaxation. However, ring A and C did not sustain the ring test as long as ring B, which was likely due to materials properties variability. This phenomenon is quite usual in restrained ring tests (*See et al. 2004, Folliard et al. 2003, Qiao et al. 2010, Radlinska et al. 2007*).

In addition, the repair mortar (RM) also exhibited superior cracking-resistance (ToC around 28 days), which indicates drying shrinkage related cracking are likely not a concern when repairing an HPC bridge deck using this material.

4.4.2 AASHTO T334

A summary of the AASHTO ring results is given in Table 4.6.

Table 4.6: Summary of time-to-cracking and stress rate of AASHTO ring tests

Mixture	Wet Curing Duration (days)	Time-to-Cracking, Days					Stress Rate, MPa/Day			
		A	B	C	Ave.		A	B	C	Ave.
HPC3	3	18.0	24.9	17.5	20.1		0.153	0.123	0.131	0.136
HPC4	14	33.1	13.9	30.0	25.6		0.107	0.201	0.100	0.136
SRA3	3	135	101	86.7	107		0.034	0.028	0.037	0.033
FLWA3	3	16.8	16.5	28.7	20.7		0.159	0.166	0.141	0.155
ST2	3	215	162	24.3	134		0.037	0.031	0.121	0.063

First of all, it can be seen that the variation in this test was larger than that of the ASTM rings. It is suggested that three rings should be done for each mixture instead of the standard recommended two rings. For example, for mixture ST2, data shows Ring A was cracked around 215 day, however no visible crack was observed at the end of test; while Ring C cracked at 25 day. The stress rate seems to be more consistent than ToC.

Due to a thicker concrete section, curing seems to have had more impact in the AASHTO rings than in the ASTM rings. Mixture HPC4, which was wet-cured for 14 days, actually outperformed the internally cured FLWA3, which was wet-cured for 3 days. The SRA mixture still showed superior cracking mitigation in the test, prolonging the ToC from less than 30 days in the control HPC mixture to over 100 days. Santosh aggregate showed the best cracking resistance, likely due to the larger aggregate size (1 inch MSA). This is also supported by a recent survey and research project (*Darwin et al. 2010*). More information about how the geometry of the ring tests can affect the results could be found in literature (*ACI Committee 231 2010*).

Another concern about the AASHTO ring test is that because of the long testing period the stress relaxation is significant. This is similar to previously discussed mixture LS in ASTM rings. For mixtures with relatively low shrinkage, the AASTHO ring test is not as sensitive as the ASTM ring test. In the KDOT research, only one out of 39 rings cracked during about 200 day testing period (*Tritsch et al. 2005*). And in the TxDOT research, some AASHTO rings lasted more than 600 days without cracking (*Folliard et al. 2003*). Detailed results can be found in Appendix B.

Based on the results in this project, the ASTM ring test is recommended over the AASHTO ring test due to: 1) more sensitive to different mixtures; 2) smaller variation, 3) quicker turnaround time, 4) smaller ring size thus easier to prepare. However, when testing concrete with larger MSA (1 inch), AASHTO rings should be used.

4.5 CRACKING POTENTIAL INDICATOR (CPI) DEVELOPED BY ASTM RING RESULTS

As outlined previously, high cracking-resistance in concrete should come from combined properties: 1) low free shrinkage; 2) relatively high tensile strength to resist tensile stress developed within concrete, and 3) relatively low modulus of elasticity so that there will be less stress development for the same amount of shrinkage. Thus, a “cracking potential indicator” (CPI) is proposed to assess cracking potential, taking account of free shrinkage as well as mechanical properties (i.e. splitting tensile strength and static modulus of elasticity). The equation is given as follows:

$$CPI = \frac{free\ shrinkage}{nominal\ tensile\ strain\ capacity} = \frac{\epsilon_{free}}{f_t/E_c} \qquad \textbf{Equation 1}$$

Where:

- ε_{free} is free shrinkage measured at 28 days from initiation of drying;
- f_t is splitting tensile strength measure at 28-day age, and;
- E_C is static modulus of elasticity measured at 28-day age.

The ratio of f_t to E_C is named nominal tensile strain capacity. This ratio does not have any physical meaning, but it is used as a relative comparison between materials. A larger nominal tensile strain capacity indicates the material is able to accommodate more tensile deformation before cracking occurs. Since 28 days is a common industrial practice used for quality control for concrete properties, it was selected as the testing age. Note that for mechanical properties tests, concrete specimens were tested at 28-day age, while for free shrinkage tests the 28 days from initiation of drying is equivalent to an age of 28 days plus the wet curing duration. Using the data listed in Table 4.2 and Table 4.4, the CPI for all mixtures was calculated using both standard cured 28-day and match cured 28-day mechanical properties as shown in Table 4.7 and Table 4.8.

Table 4.7: Summary of calculated CPI

Mixture	Curing Duration (days)	28-day free shrinkage (microstrain)	Stress Rate (MPa/day)	ToC (Days)	CPI (Standard cured)	CPI (Match cured)
HPC1	3	600	0.344	4.9	4.02	4.19
HPC2	14	550	0.369	4.2	3.89	3.43
SRA1	3	337	0.087	17.0	2.38	-
SRA2	14	447	0.112	14.2	3.46	3.00
FLWA1	3	535	0.245	6.9	3.48	-
FLWA2	14	663	0.254	7.7	3.80	3.59
SYN1	14	345	0.081	15.9	2.75	2.48
SYN2	14	287	0.105	17.0	1.93	2.01
SYN3	14	287	0.111	13.3	2.09	1.73
OPCA	14	600	0.315	5.0	5.26	4.63
OPCB	14	557	0.254	4.1	4.89	-
LS	14	380	0.082	>41	3.16	2.36
BD	14	860	0.304	6.5	10.01	7.15
MD	14	610	0.257	4.1	6.71	5.20
ST1	3	500	0.225	10.3	3.97	3.62
RM	3	447	0.073	28.0	-	2.24

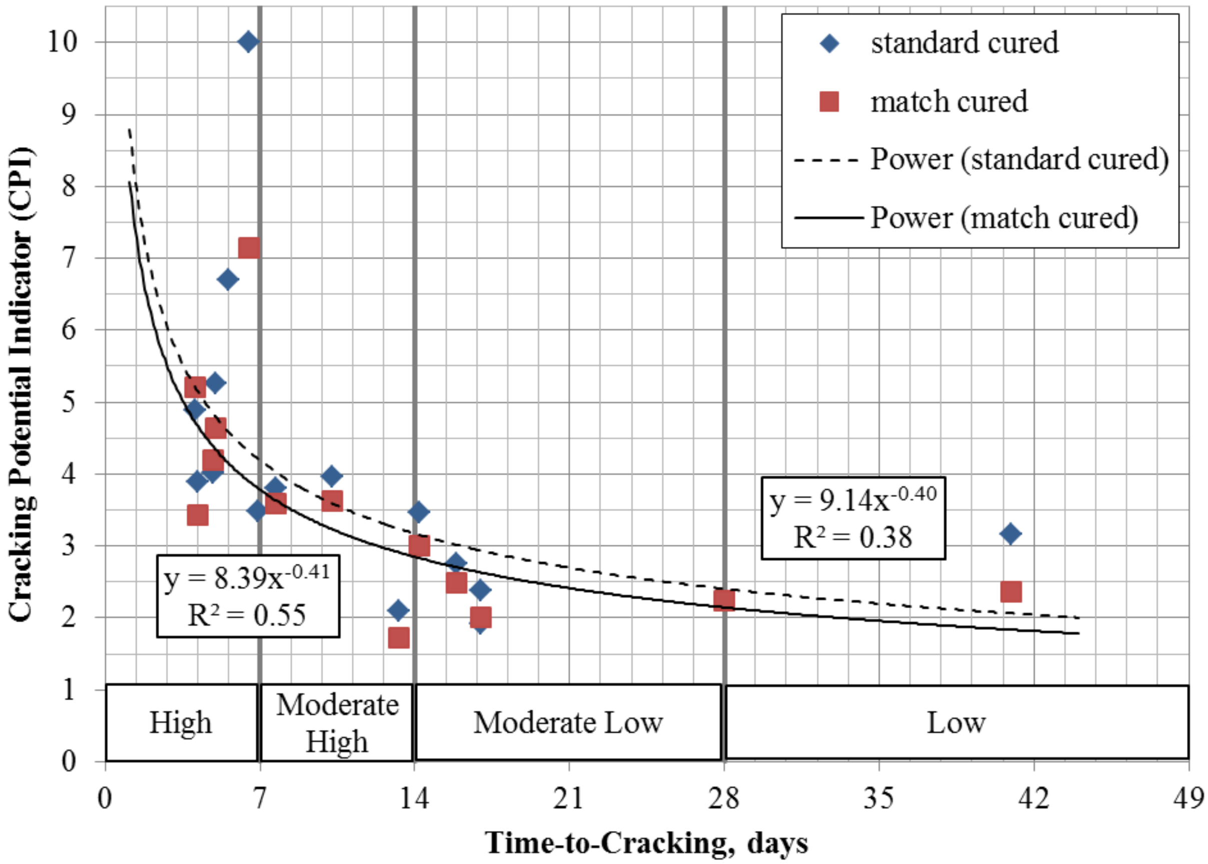

Figure 4.8: CPI versus time-to-cracking

Figure 4.8 shows the relationship between CPI and time-to-cracking. According to the cracking potential classification given in Table 2.1, the chart was divided into four zones based on time-to-cracking. A general trend can be observed that mixtures with lower CPI tend to fall into a lower cracking risk zone. The power relations are also given in the chart with equations and correlation coefficients. The standard and match cured CPI for BD aggregate appears to be an outlier due to a high free shrinkage. One interesting finding is that CPI calculated using the match cured (R^2=0.55) concrete properties showed better correlation with time-of cracking than the CPI calculated using standard curing or "28-day wet cure" (R^2=0.38). This is likely due to concrete samples that were match cured in the same conditions and for the same durations as the ring specimens. Thus this more accurately represented the condition of the concrete in the rings. As a result, match cured concrete samples, when available, should be used to estimate the cracking risk of a given concrete mixture if this proposed CPI method is used. As a result, Figure 4.9 shows the relationship between the CPI and the stress rate for the match cured samples.

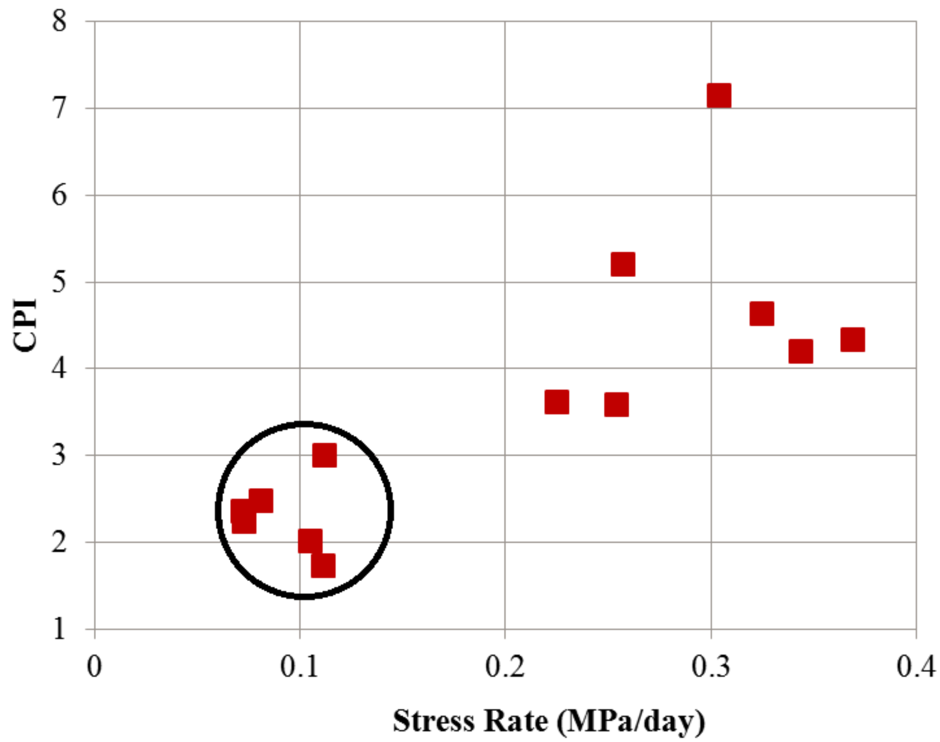

Figure 4.9: CPI (match cured) versus stress rate

Two bars were placed on Figure 4.8 to divide the plot into four zones. The left upper zone could be recognized as a high cracking risk zone, with all mixtures of ToC less than 14 days. While the right lower corner is the low cracking risk zone, with all mixtures of ToC more than 14 days and CPI lower than 3.0. This is further supported in Figure 4.9, which shows that all mixtures with CPI lower than 3.0 (in the circle) had a stress rate around 0.1 Mpa/day (15 psi/day), indicating a low cracking risk per ACI 231. Therefore, a preliminary cracking potential classification based on the CPI is proposed in Table 4.8. The authors emphasize that the threshold values shown in Table 4.8 should be considered preliminary due to the low coefficient of correlation (less than 0.6) shown in the relationships in Figure 4.8. Further data would likely improve the confidence in the threshold values.

Table 4.8: Cracking potential classification based on the CPI

Cracking Potential Indicator (CPI)	Potential for Cracking
CPI $\geq$ 4.0	High
3.0 $\leq$ CPI < 4.0	Moderate
CPI < 3.0	Low

According to the proposed CPI, a combination of high tensile strength and low modulus of elasticity is preferred. However, these two properties are usually not independent of each other; therefore, it might be difficult to manipulate tensile strength and modulus of elasticity in practice to achieve desired values. Generally speaking, the coarse aggregate type (round vs. angular, different mineralogy/chemical composition) could impact the tensile strength and modulus of elasticity of the coarse aggregate. But manipulating this parameter may also be challenging due to use of local aggregates. Therefore, the factor that could most significantly be modified to reduce the cracking potentials is still free drying shrinkage.

4.6 CPI OR FREE SHRINAKGE?

A central question still needs to be answered: does CPI work better than free shrinkage in identifying cracking risk of mixture designs? Figure 4.10 gives a comparison between CPI and 28-day free shrinkage versus ToC.

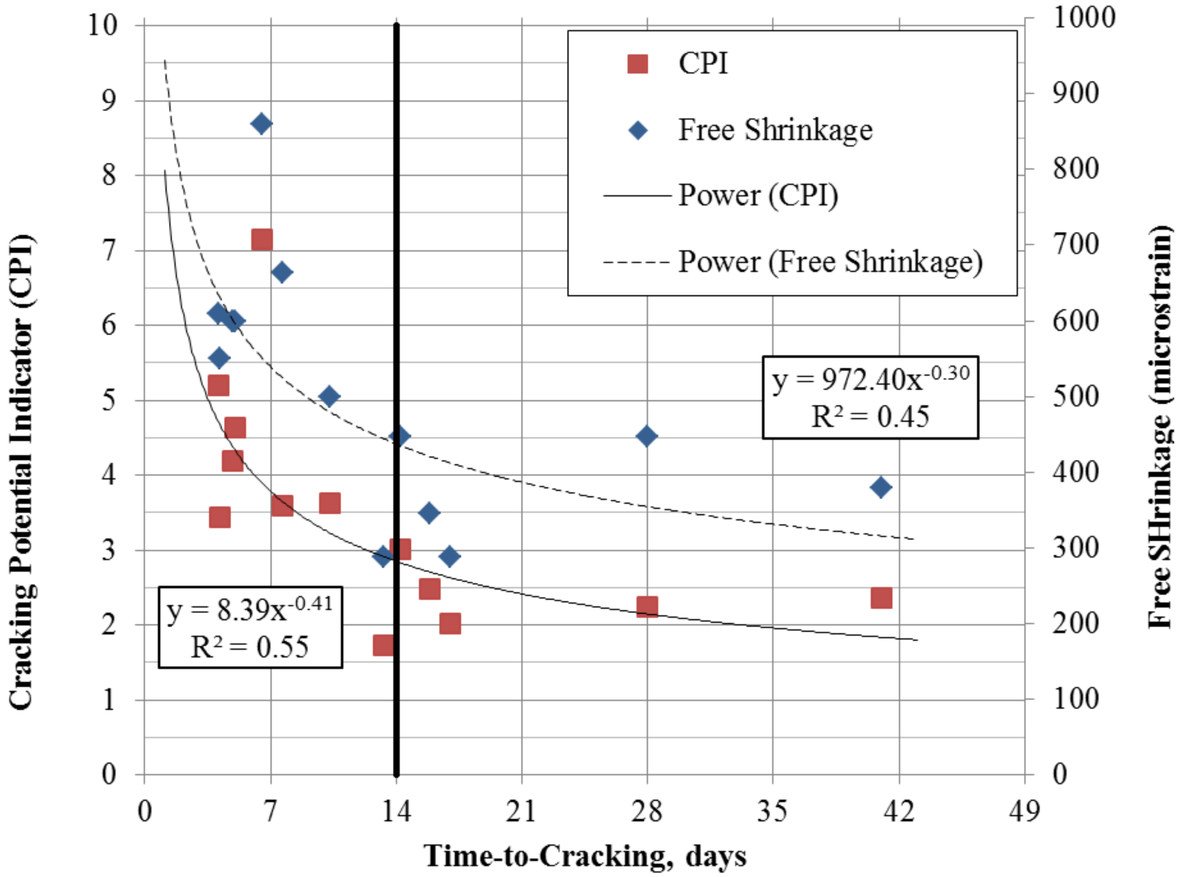

Figure 4.10: CPI (Match cured) versus time-of-cracking

Figure 4.10 shows that the CPI (match cured) exhibits less scatter than the free shrinkage data, with a correlation coefficient of 0.55 compared to 0.45. Therefore, it may also be reasonable to use free shrinkage to evaluate the potential for cracking risk and expect similar accuracy compared to the CPI. By comparing time-to-cracking with free shrinkage for all mixtures (as shown in Figure 4.10), a 28-day free shrinkage limit of 450 microstrain is recommended.

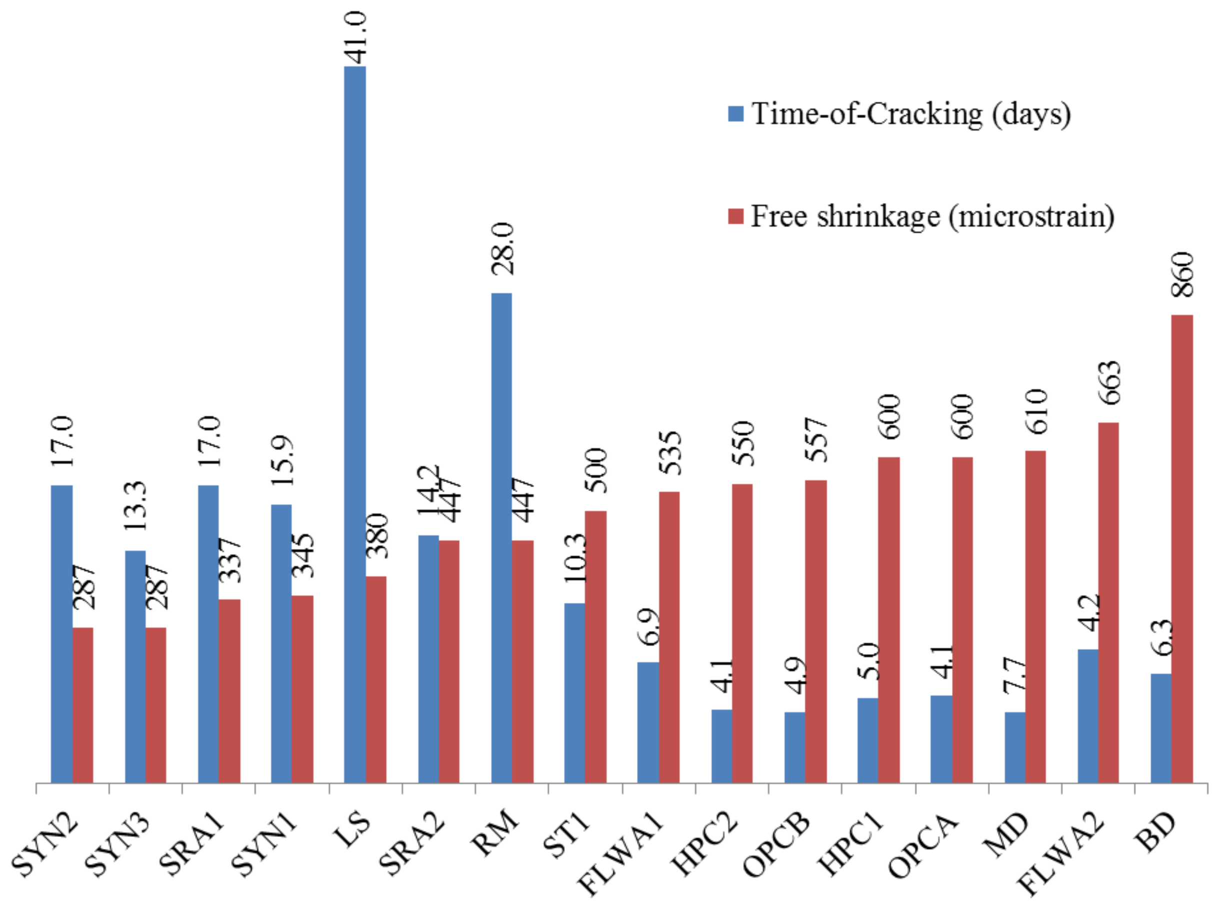

Figure 4.11: Comparison of free shrinkage with time-of-cracking in all mixtures

In Figure 4.11, all 16 mixtures were listed from the lowest shrinkage mixture (SYN2) to the highest (BD), by plotting time-of-cracking and free shrinkage for the same mixtures next to each other. To better illustrate this contrast, an arbitrary scaling factor was selected (14 day = 450 microstrain). For instance the RM mixture has a free shrinkage of 447 microstrain at 28 days. Since this mixture lasted approximately twice as long as the reference (14 day = 450 microstrain) the time to cracking bar (in blue) is scaled approximately 2x. In this way it allows the data in Figure 4.11 to be more easily interpreted, especially for the small values of time to cracking age. It is quite interesting to find that all mixtures with lower than 450 microstrain free shrinkage at 28 days from initiation of drying have greater than or approximately equal to 14-day time-of-cracking in the ASTM ring test, which would be considered moderate low cracking risk. The research shows that the SYN2, SYN3, SRA1, SYN1, LS, SRA2, and RM would be expected to perform reasonably well in the field with respect to cracking related to drying shrinkage. Therefore, a 450 microstrain free shrinkage at 28 days from initiation of drying seems to be a reasonable shrinkage limit for future ODOT bridge deck concrete mixture designs.

5.0 CONCLUSIONS AND RECOMENDATIONS

5.1 CONCLUSIONS

In the US, cracking in bridge decks causes shortened service life of the structure, and increased burdens to state DOTs through maintenance, retrofit and inspection. Recent studies on drying shrinkage and cracking issues on bridge decks in the US were summarized herein. From a testing perspective, several well-established relatively simple tests exist for assessing shrinkage and/or cracking risk of concrete mixtures (ASTM C157 and ASTM/AASHTO ring tests). The current understanding of high-cracking-resistance concrete is that the concrete should have low free shrinkage, low early-age modulus of elasticity, and a high tensile (or flexural) strength. While these standard tests exist and have been used extensively in both research and practice, there is a significant gap in the implementation of shrinkage limits/thresholds used to interpret the results of such tests. The goal of this research project was to identify such limits/thresholds and make recommendations on the use of existing/augmented and/or new testing methods to enable ODOT to receive highly crack resistant concrete bridge decks.

This research focused on using mechanical properties and free shrinkage (relatively straightforward and standard tests for a contractor/testing laboratory) in comparison to restrained ring tests (ASTM C 1581 and AASHTO T334). In this research, sixteen (16) mixtures using the ASTM C1581 ring test were evaluated. Another five (5) mixtures using the AASHTO T334 ring test were investigated. Several general conclusions are listed as follows:

- According to the results of ASTM C1581 restrained ring tests, by incorporating SRA alone or a synergistic mixture of SRA and FLWA, the cracking resistance of ODOT HPC was significantly improved. The HPC with a combination of SRA and LWFA showed the most significant benefits in improving the cracking resistance.

- The results showed that the HPC mixtures using local siliceous river gravel had significantly higher shrinkage and cracking propensity than a corresponding HPC mixture using limestone.

- The ASTM C1581 ring test is a comprehensive way to evaluate the cracking performance of HPC mixtures. A “cracking potential indicator” (CPI) calculated from free shrinkage, splitting tensile strength, and modulus of elasticity values was proposed in this study. A reasonably good correlation was found between CPI and ring test results. Data analysis showed that a CPI less than 3.0 generally indicates a low cracking risk.

- The AASHTO T334 restrained ring test tends to be less sensitive to the ASTM rings. While the control HPC mixtures did exhibit cracking in this test, it was difficult to compare the efficacy of different shrinkage/cracking reduction methods using this test method since the other rings had such long durations to cracking or did not exhibit any cracking at all.

- One potential benefit of the CPI is that it is a universal approach to specifying crack resistance concrete. Rather than a singular limit, which likely only could be applied to certain mixture designs, the CPI can be easily applied universally using other “local” materials. This represents a significant outcome from this research project for other State DOTs, Transportation Agencies and owners of concrete bridge decks. The CPI may even have application (with appropriate modifications) to other types of structural/paving elements

5.2 RECOMMENDATIONS

A list of screening tests recommended in evaluating cracking risk of certain concrete mixtures is as follows: [ranking from highest accuracy (1) to lowest accuracy (4)]:

1. **Ring tests** (ASTM C1581 or AASHTO T334): ASTM C1581 rings are recommended over AASHTO rings due to increased sensitivity to different mixture modifications. However, AASHTO rings should be used when larger aggregates (1” MSA) are used.

2. **CPI (match cured)**: Free shrinkage should be monitored by the ASTM C157 test, and mechanical properties (compressive strength, splitting tensile strength, and modulus of elasticity) should be tested on match cured cylinder samples (samples cured with the same conditions as the concrete in the field). These values are then used in the CPI approach outlined herein to delineate between different cracking risks. The decision of acceptable cracking risk is left to the owner/specifier.

3. **Free shrinkage limit**: 450 microstrain is the recommended limit for ODOT bridge deck mixture.

4. **CPI (standard 28-day wet cure)**: Free shrinkage should be monitored by the ASTM C157 test, and mechanical properties (compressive strength, splitting tensile strength, and modulus of elasticity) tested on standard 28-day wet cured cylinder samples (samples cured in laboratory fog room).

5.3 FUTURE RESEARCH

Based on this research and the previous SPR711 research, the standard ODOT HPC mixture, using aggregates from the Corvallis area, Bend area and Medford area has inherently high free shrinkage, which is believed to be one of the main contributing factors to observed cracking in the field. Further research on shrinkage reduction and crack control is recommended:

- Coarse aggregate sourcing seems to have a significant impact on shrinkage and cracking. Simply modifying the source of the coarse aggregate is difficult and thus further work is needed to identify impacts of coarse aggregate and changes that can be made to still use locally available materials. This may involve the use of fibers to control any cracking that develops due to high shrinkage

- Apply more effective/aggressive shrinkage mitigation techniques such as:
    - Higher FLWA content;
    - Use of shrinkage reducing admixtures (SRA)
    - Combined techniques (synergy of FLWA and SRA, SRA+low shrinkage aggregate).

- Apply cracking control techniques such as:
    - Synthetic fibers;
    - Combined techniques (fiber + SRA, etc)

- Revise the current ODOT HPC mixture for concrete bridge deck to aim for a low-shrinkage and low cracking mixture design. This may involve:
    - Reducing cement contents
    - Increasing the w/cm ratio
    - Shrinkage compensating concrete (e.g. additions of Type K cements, etc.)
    - Investigations into a dual lift approach (e.g. for an 8 inch thick deck), the lower 4 inches could be a more standard performance concrete mixture and the upper 4 inches could be an ultra-high performance mixture with a specified coarse aggregate, fibers, SRA, FLWA, shrinkage compensating cements or combinations thereof. This may represent an approach to keep the construction of the decks economically viable for upfront costs while ensuring a long-term durability of the deck

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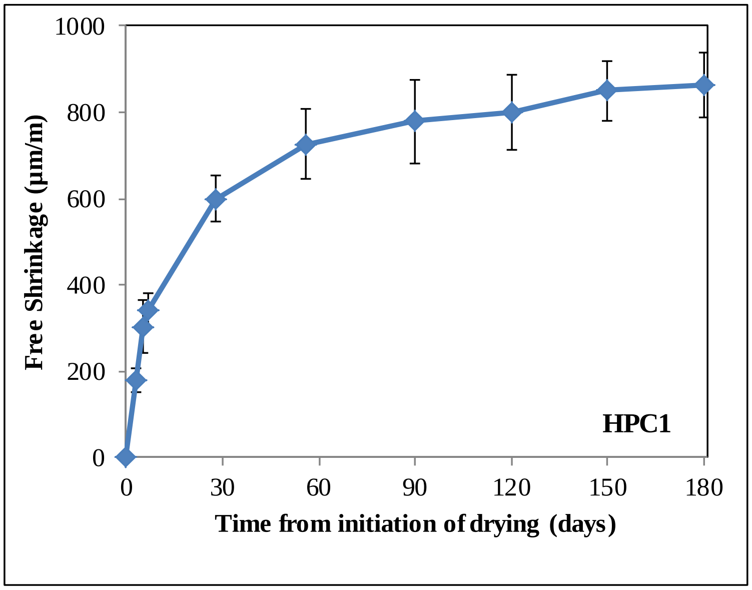
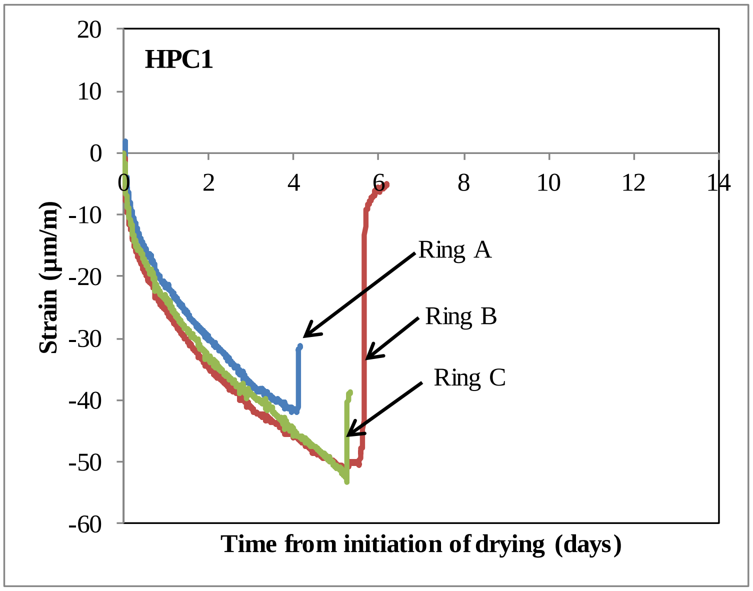
APPENDIX A – ASTM TESTING RESULTS SUMMARY

Mix ID:	**HPC1**	Cast date:	3/9/2012	Curing time (days):	**3**
Mix description:	ODOT HPC control mix				
Fresh properties					
Batch size(cu ft):	3.0	w/cm:	0.37	Temperature (°C):	21.4
Slump (in):	5	Air content (%):	6.0	Unit weight (pcf):	144.1
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
28.8	3.42	22.9	30.3	3.49	24.4



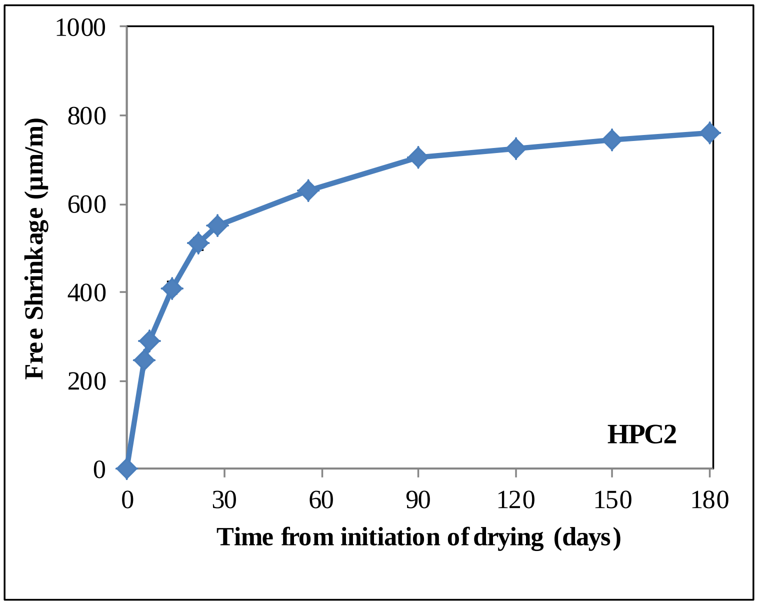
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
3	180	26.5
5	303	60.3
7	340	40.0
28	**600**	52.9
56	727	81.4
90	780	96.4
120	800	87.2
150	850	70.0
180	863	75.7



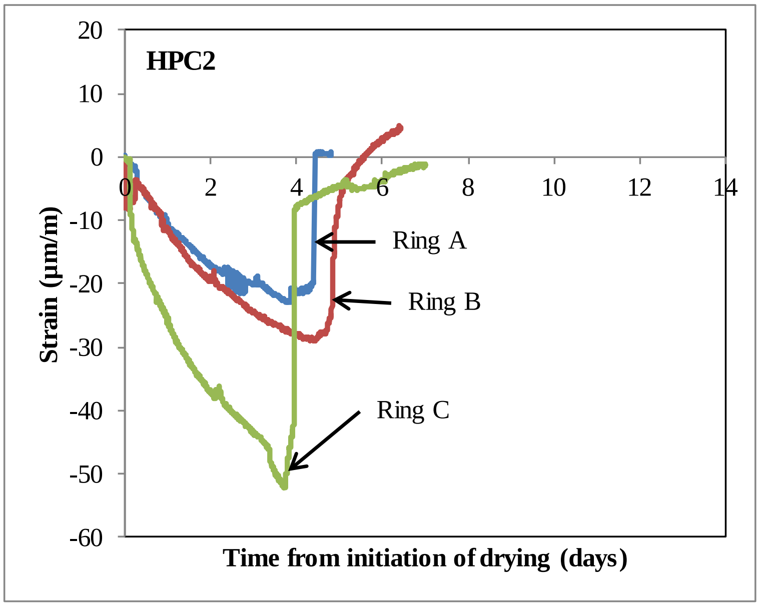
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	4.0	0.380	**High**
Ring B	5.5	0.315	
Ring C	5.2	0.338	
Average	**4.9**	**0.344**	

CPI	
Standard Cure	Mathed Cure
4.02	**4.19**

Mix ID:	HPC2	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 (%):	4.5	Unit weight (pcf):	146.5
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
35.4	4.06	2.9	39.9	4.40	27.5



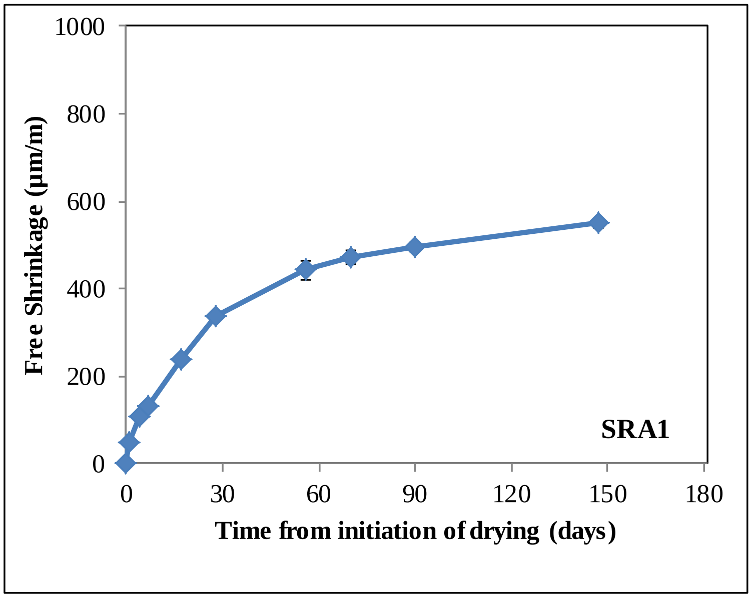
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
5	245	7.1
7	290	0.0
14	410	14.1
22	510	14.1
28	**550**	0.0
56	630	7.1
90	705	7.0
120	725	7.1
150	745	7.1
180	760	0.0



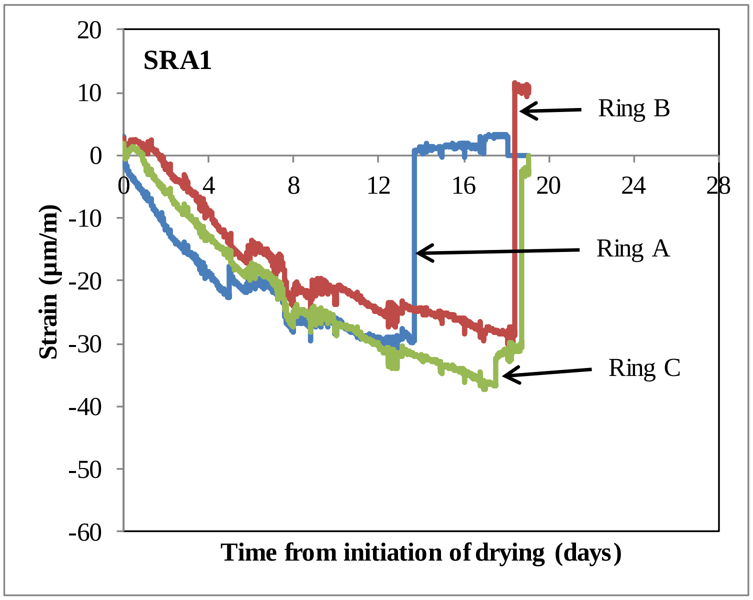
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	4.4	0.343	**High**
Ring B	4.6	0.281	
Ring C	3.6	0.482	
Average	**4.2**	**0.369**	

CPI	
Standard Cure	Mathed Cure
3.89	**3.43**

Mix ID:	SRA1	Cast date:	11/9/2011	Curing time (days):	3
Mix description:	ODOT HPC control mix + 2% SRA				
Fresh properties					
Batch size(cu ft):	2.7	w/cm:	0.37	Temperature (°C):	21.6
Slump (in):	9	Air content (%):	5.5	Unit weight (pcf):	141.4
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
33.2	3.97	28.0	-	-	-



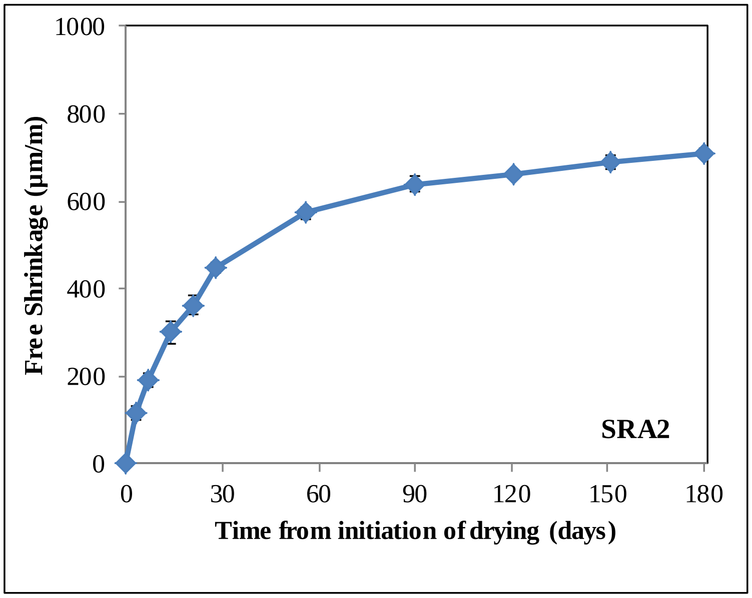
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	5.8
1	47	0.0
4	110	5.8
7	133	5.8
17	237	5.8
28	**337**	5.8
56	443	20.8
70	473	15.3
90	497	11.5
147	550	10.0



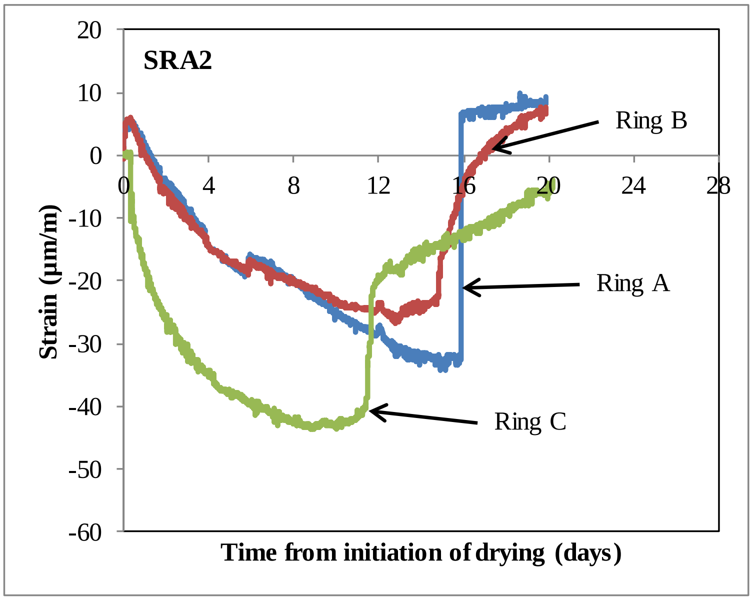
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	13.9	0.094	**Low**
Ring B	18.4	0.073	
Ring C	18.8	0.094	
Average	**17.0**	**0.087**	

CPI	
Standard Cure	Mathed Cure
2.38	**-**

Mix ID:	SRA2	Cast date:	4/26/2012	Curing time (days):	14
Mix description:	ODOT HPC control mix + 2% SRA				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	20.8
Slump (in):	5 1/2	Air content (%):	4.5	Unit weight (pcf):	145.4
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
36.4	3.78	29.3	39.1	4.08	27.4



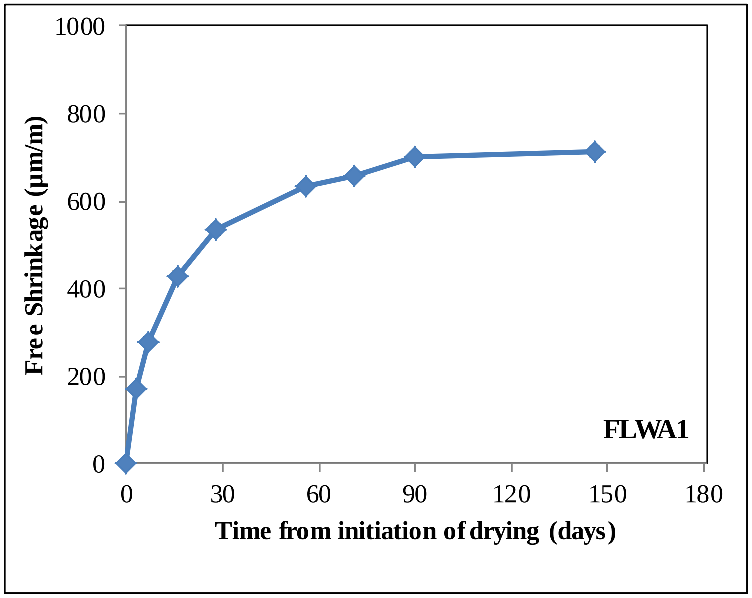
Time	Shrinkage (µm/m)	Std. Dev. (µm/m)
0	0	0.0
3	117	15.3
7	190	15.3
14	300	26.5
21	363	20.8
28	**447**	11.5
56	573	15.3
90	640	17.3
121	663	5.8
151	690	17.3
180	710	10.0



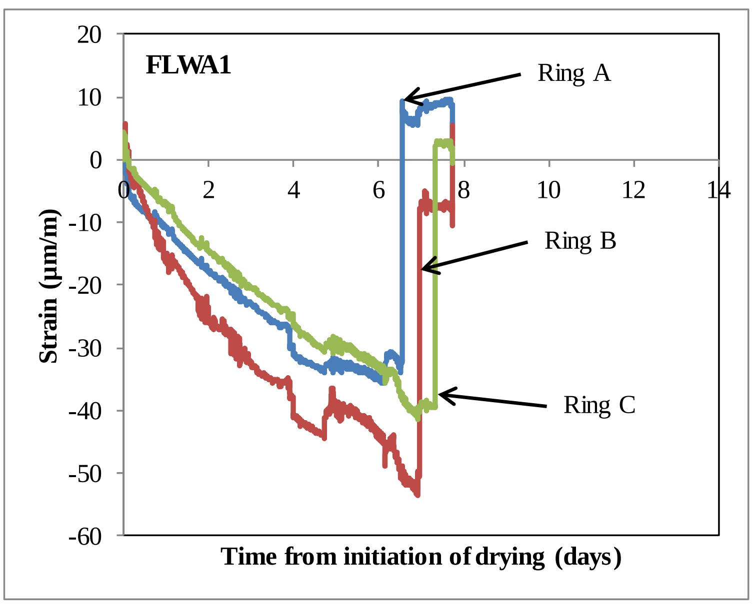
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	16.1	0.104	**Moderate Low**
Ring B	14.9	0.093	
Ring C	11.6	0.139	
Average	**14.2**	**0.112**	

CPI	
Standard Cure	Mathed Cure
3.46	**3.00**

Mix ID:	FLWA1	Cast date:	11/10/2011	Curing time (days):	3
Mix description:	ODOT HPC mix with partial sand replacement by prewetted FLWA				
Fresh properties					
Batch size(cu ft):	2.7	w/cm:	0.37	Temperature (°C):	20.4
Slump (in):	8 1/2	Air content (%):	7.5	Unit weight (pcf):	138.4
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
36.6	3.72	24.2	-	-	-



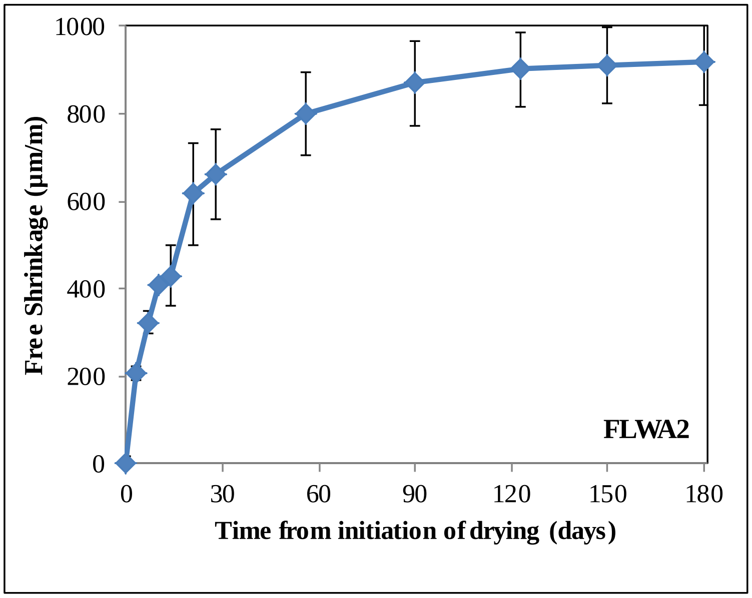
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
3	173	5.8
7	280	10.0
16	430	10.0
28	**535**	11.5
56	633	5.8
71	657	5.8
90	703	10.0
146	713	11.5



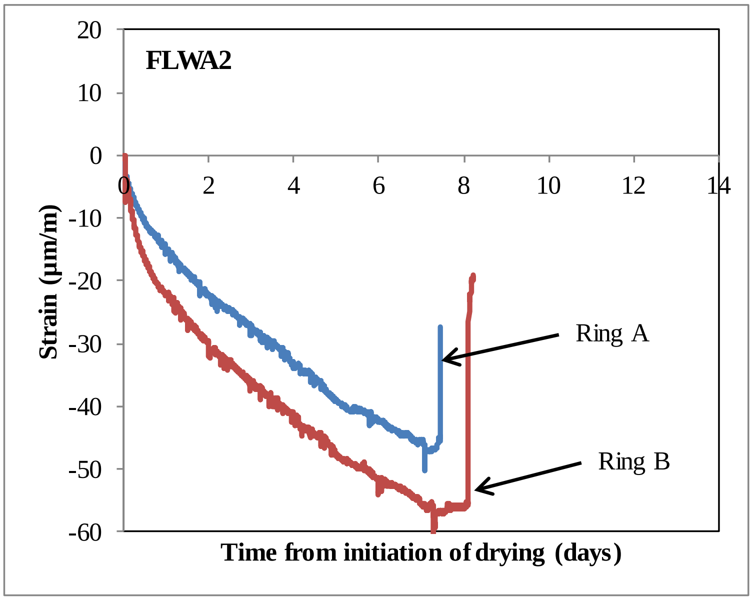
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	6.5	0.238	**Moderate High**
Ring B	7.0	0.213	
Ring C	7.3	0.284	
Average	**6.9**	**0.245**	

CPI	
Standard Cure	Mathed Cure
3.48	**-**

Mix ID:	FLWA2	Cast date:	4/19/2012	Curing time (days):	14
Mix description:	ODOT HPC mix with partial sand replacement with prewetted FLWA				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	22.0
Slump (in):	8	Air content (%):	3.0	Unit weight (pcf):	143.9
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
45.4	5.17	29.6	53.5	5.48	29.7



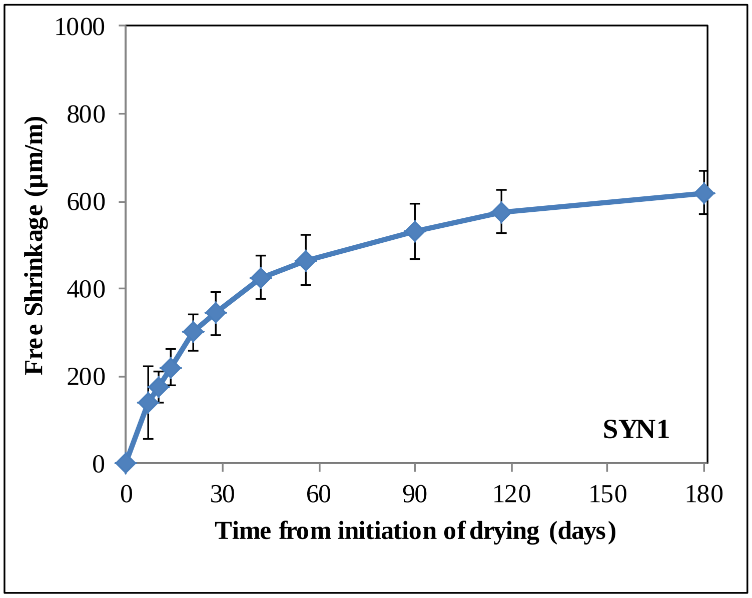
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	15.3
3	207	15.3
7	323	25.2
10	407	5.8
14	430	70.0
21	617	117.2
28	**663**	102.1
56	800	95.4
90	870	96.4
123	903	85.0
150	910	86.6
180	917	96.1



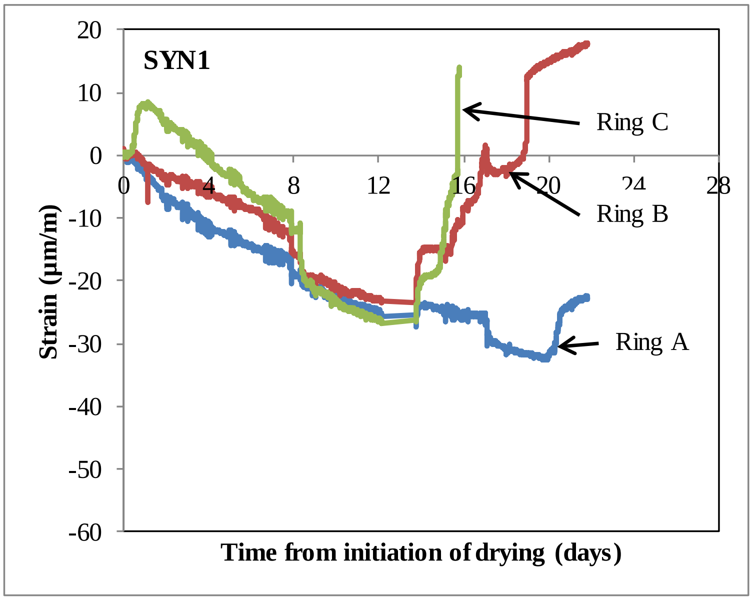
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	7.4	0.245	**Moderate High**
Ring B	7.9	0.263	
Ring C	-	-	
Average	**7.7**	**0.254**	

CPI	
Standard Cure	Mathed Cure
3.80	**3.59**

Mix ID:	SYN1	Cast date:	11/20/2012	Curing time (days):	14
Mix description:	ODOT HPC mix with partial sand replacement by prewetted FLWA + 2% SRA				
Fresh properties					
Batch size(cu ft):	3.1	w/cm:	0.37	Temperature (°C):	20.0
Slump (in):	6	Air content (%):	6.0	Unit weight (pcf):	136.4
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
26.1	2.76	22.0	24.2	2.93	21.1



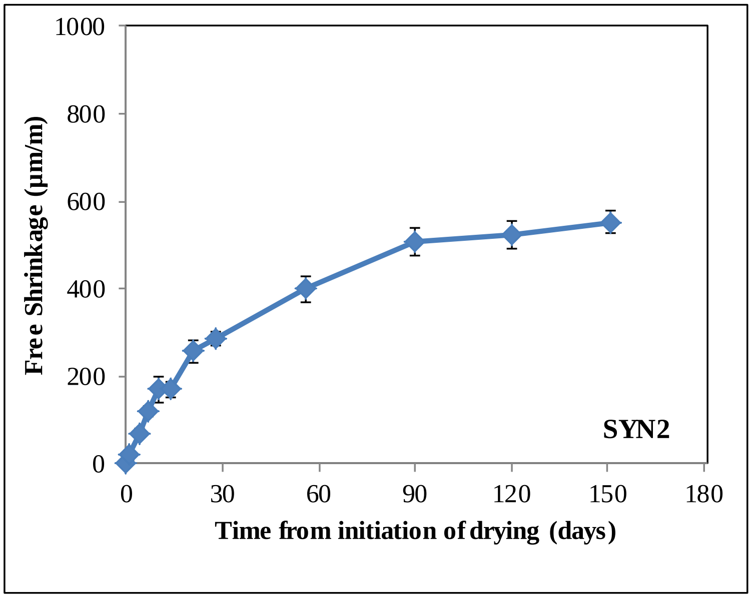
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
7	140	83.3
10	175	35.4
14	220	42.4
21	300	42.4
28	**345**	49.5
42	425	49.5
56	465	56.6
90	530	63.6
117	575	49.5
180	620	49.5



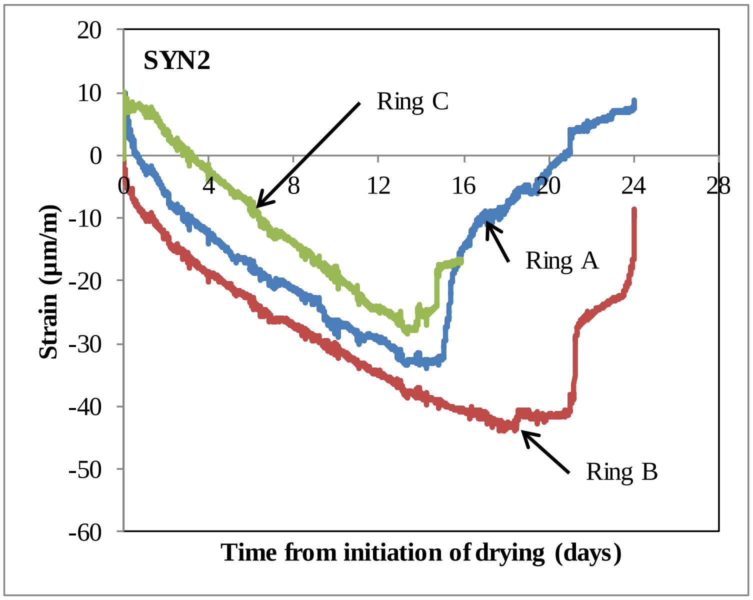
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	19.7	0.115	**Low**
Ring B	14.0	0.070	
Ring C	14.0	0.060	
Average	**15.9**	**0.081**	

CPI	
Standard Cure	Mathed Cure
2.75	**2.48**

Mix ID:	SYN2	Cast date:	4/5/2013	Curing time (days):	14
Mix description:	ODOT HPC mix with partial sand replacement by water-soaked FLWA + 2% SRA				
Fresh properties					
Batch size(cu ft):	3.3	w/cm:	0.37	Temperature (°C):	24.8
Slump (in):	5	Air content (%):	2.5	Unit weight (pcf):	144.3
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
43.5	4.05	27.2	40.3	4.02	28.2



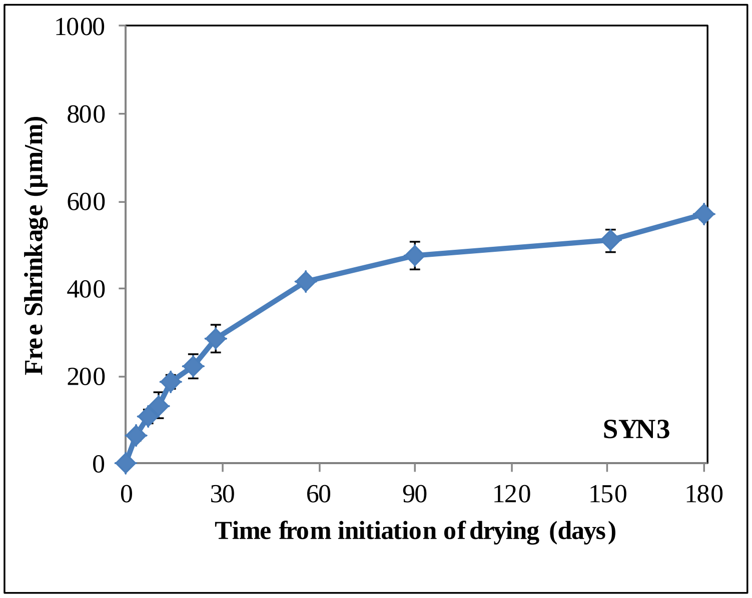
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
1	20	10.0
4	70	10.0
7	120	10.0
10	170	30.0
14	170	17.3
21	257	25.2
28	**287**	15.3
56	400	28.9
90	507	32.1
120	523	30.6
151	553	25.2



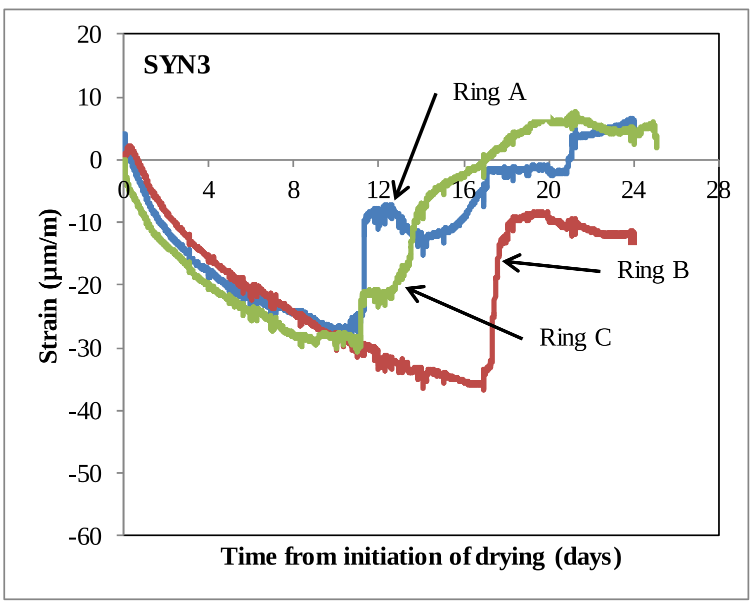
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	15.1	0.117	**Moderate Low**
Ring B	21.1	0.082	
Ring C	14.7	0.114	
Average	**17.0**	**0.105**	

CPI	
Standard Cure	Mathed Cure
1.93	**2.01**

Mix ID:	SYN3	Cast date:	1/18/2013	Curing time (days):	14
Mix description:	ODOT HPC mix with partial sand replacement by SRA solution-soaked FLWA				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	19.2
Slump (in):	5	Air content (%):	2.5	Unit weight (pcf):	142.8
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
38.3	3.71	27.0	34.0	4.39	28.2



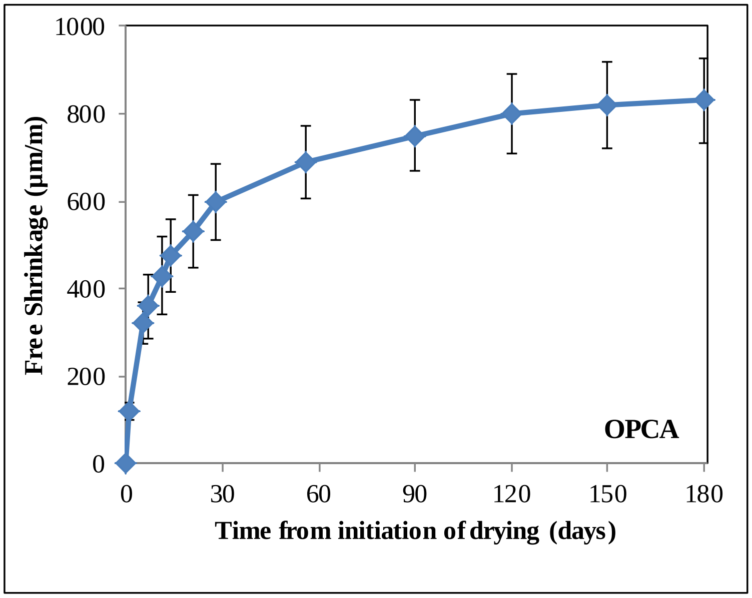
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
3	63	11.5
7	107	15.3
10	133	28.9
14	187	15.3
21	223	28.9
28	**287**	32.1
56	417	5.8
90	477	32.1
151	510	26.5
180	570	10.0



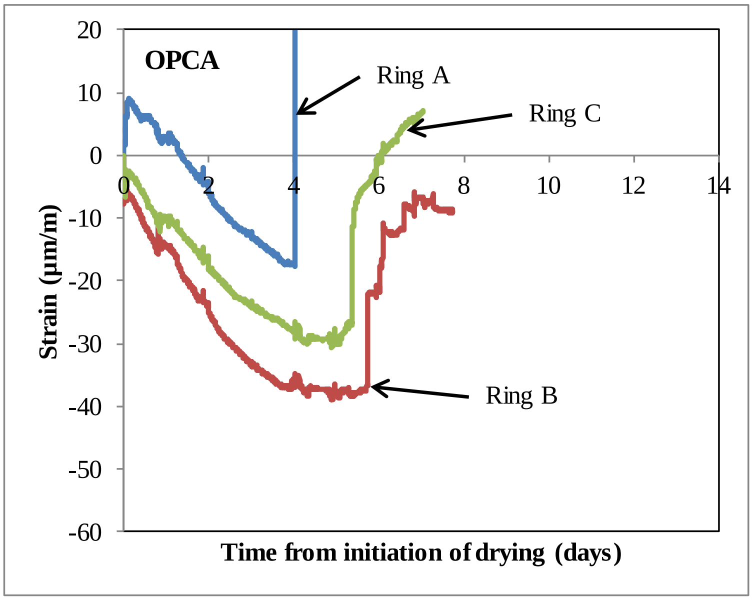
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	11.3	0.106	**Moderate Low**
Ring B	17.3	0.111	
Ring C	11.2	0.115	
Average	**13.3**	**0.111**	

CPI	
Standard Cure	Mathed Cure
2.09	**1.73**

Mix ID:	OPCA	Cast date:	7/18/2012	Curing time (days):	14
Mix description:	OPC mix (no SCMs)				
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 (MPa)	ft (MPa)	E (GPa)
44.7	3.67	32.2	45.7	4.29	33.1



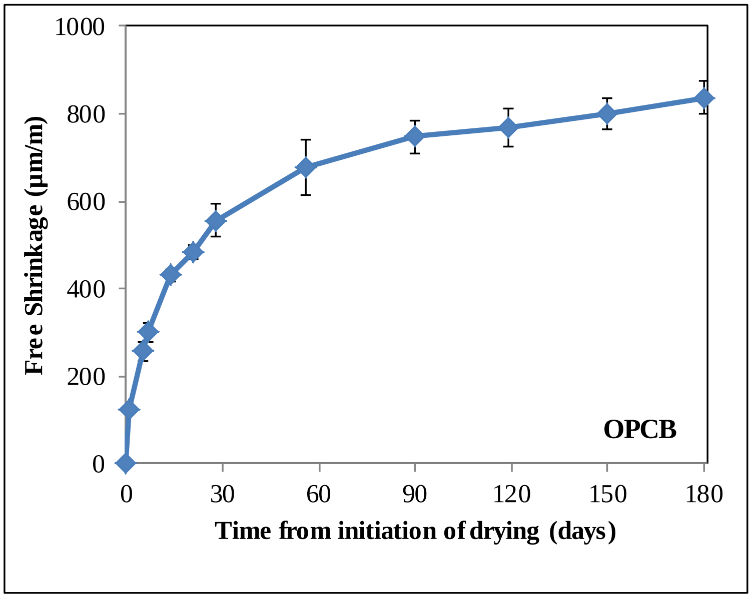
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
1	120	20.0
5	323	47.3
7	360	72.1
11	430	88.9
14	477	83.9
21	533	83.3
28	**600**	87.2
56	690	81.9
90	750	81.9
120	800	91.7
150	820	98.5
180	830	98.5



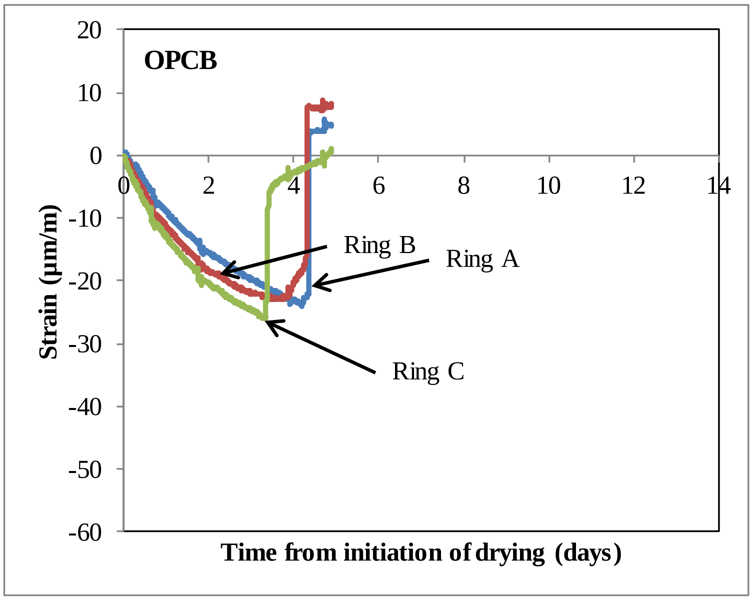
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	4.0	0.278	**Moderate High**
Ring B	5.6	0.383	
Ring C	5.3	0.314	
Average	**5.0**	**0.325**	

CPI	
Standard Cure	Mathed Cure
5.26	**4.63**

Mix ID:	OPCB	Cast date:	7/12/2012	Curing time (days):	14
Mix description:	OPC mix (no SCMs) higher w/cm				
Fresh properties					
Batch size(cu ft):	3.3	w/cm:	0.42	Temperature (°C):	25.4
Slump (in):	2 1/4	Air content (%):	3.5	Unit weight (pcf):	148.4
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
34.5	3.42	30.0	-	-	-



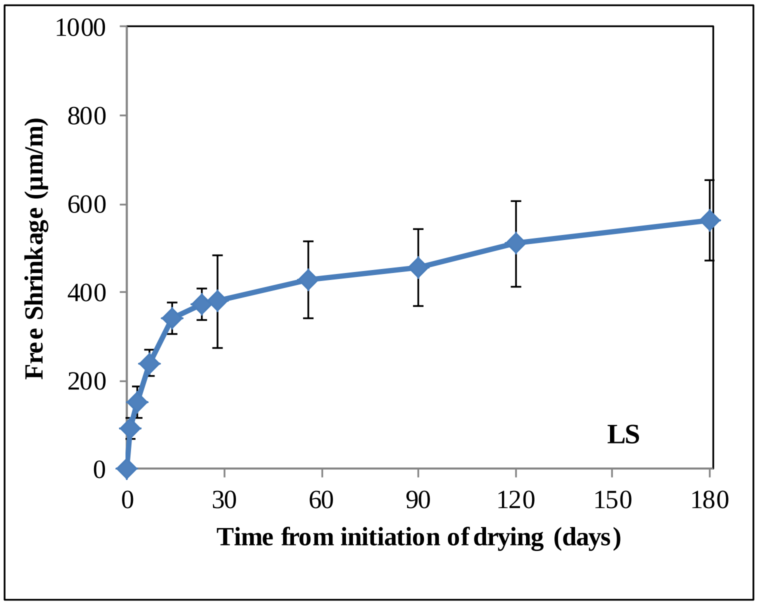
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
1	123	5.8
5	257	20.8
7	300	20.0
14	431	15.3
21	483	15.3
28	**557**	37.9
56	677	64.3
90	747	37.9
119	770	43.6
150	800	36.1
180	837	37.9



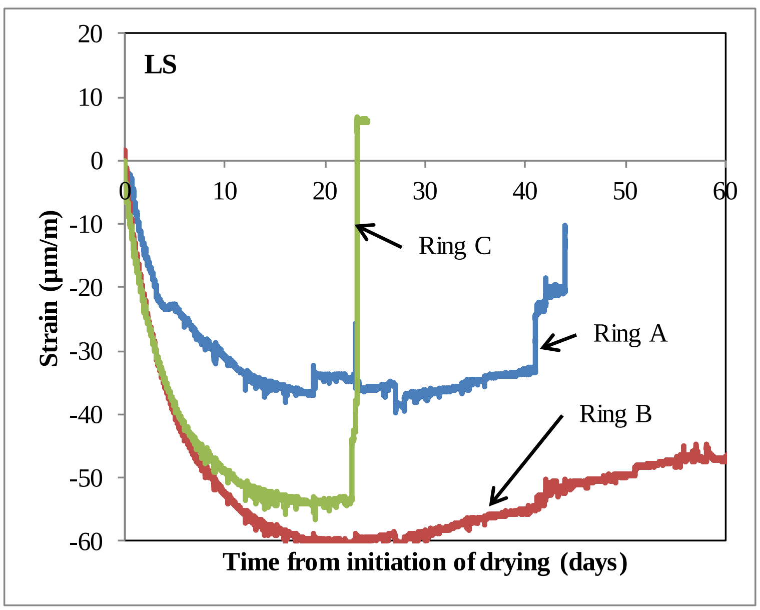
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	4.2	0.257	**Moderate High**
Ring B	4.6	0.266	
Ring C	3.6	0.238	
Average	**4.1**	**0.254**	

CPI	
Standard Cure	Mathed Cure
4.89	**-**

Mix ID:	**LS**	Cast date:	1/16/2013	Curing time (days):	**14**
Mix description:	ODOT HPC control mix with limestone coarse aggregate				
Fresh properties					
Batch size(cu ft):	3.8	w/cm:	0.37	Temperature (°C):	19.8
Slump (in):	3 1/4	Air content (%):	7.0	Unit weight (pcf):	138.3
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
34.2	3.90	32.4	35.9	4.12	25.6



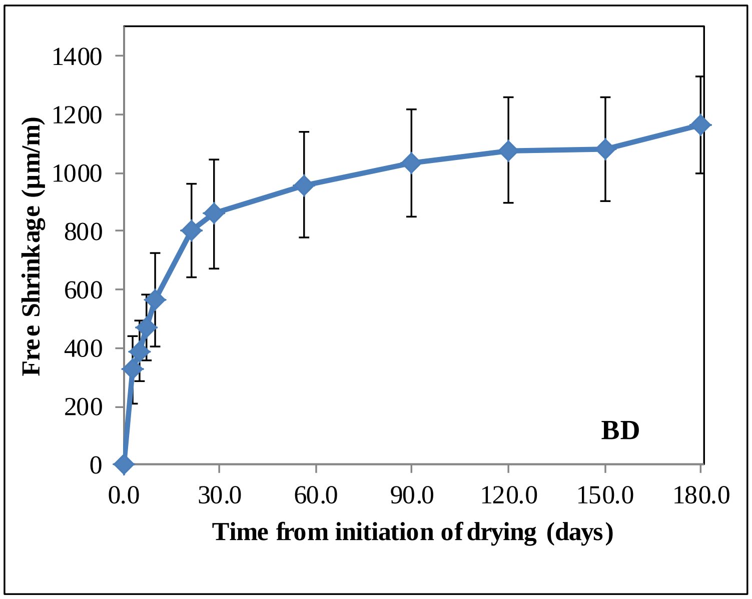
Time	Shrinkage (µm/m)	Std. Dev. (µm/m)
0	0	0.0
1	93	23.1
3	153	35.1
7	240	30.6
14	343	35.1
23	373	35.1
28	**380**	103.9
56	430	87.4
90	457	87.4
120	510	95.4
180	563	90.0



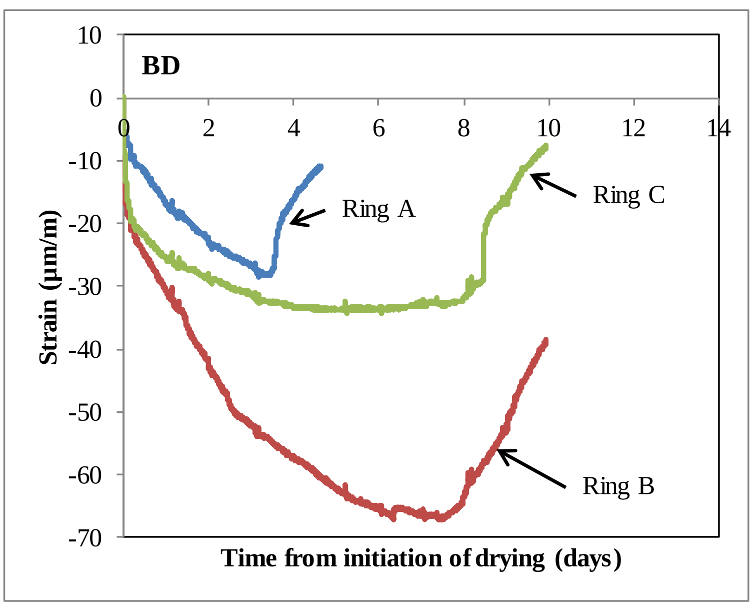
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	40.9	0.045	**Low**
Ring B	no crack @ 60 day	≈0.10	
Ring C	23.1	0.099	
Average	**>41**	**0.082**	

CPI	
Standard Cure	Mathed Cure
3.16	**2.36**

Mix ID:	BD	Cast date:	7/10/2012	Curing time (days):	14
Mix description:	ODOT HPC control mix with Bend coarse aggregate				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	25.4
Slump (in):	3 3/4	Air content (%):	7.0	Unit weight (pcf):	141.9
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
24.5	2.68	31.2	27.5	3.27	27.2



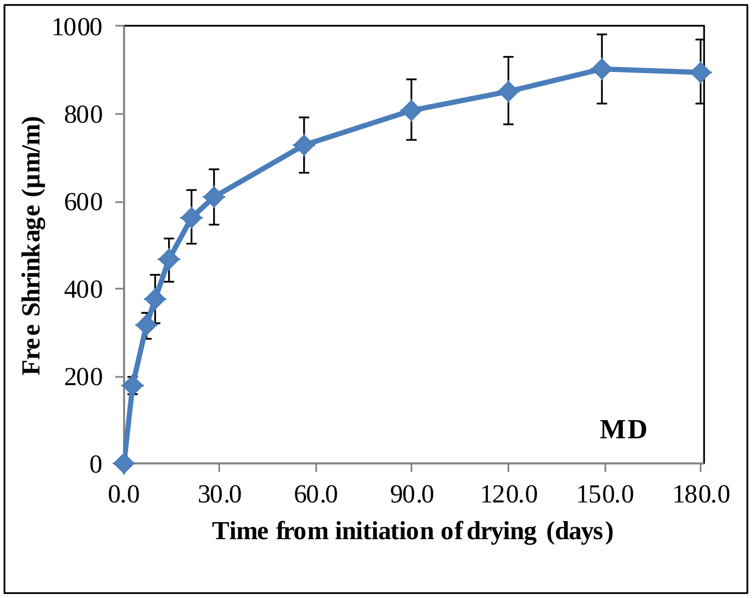
Time	Shrinkage (µm/m)	Std. Dev. (µm/m)
0	0	0.0
3	327	115.0
5	390	105.8
7	473	112.4
10	567	160.4
21	803	159.5
28	**860**	185.2
56	960	183.4
90	1033	185.8
120	1077	181.8
150	1083	179.0
180	1167	165.0



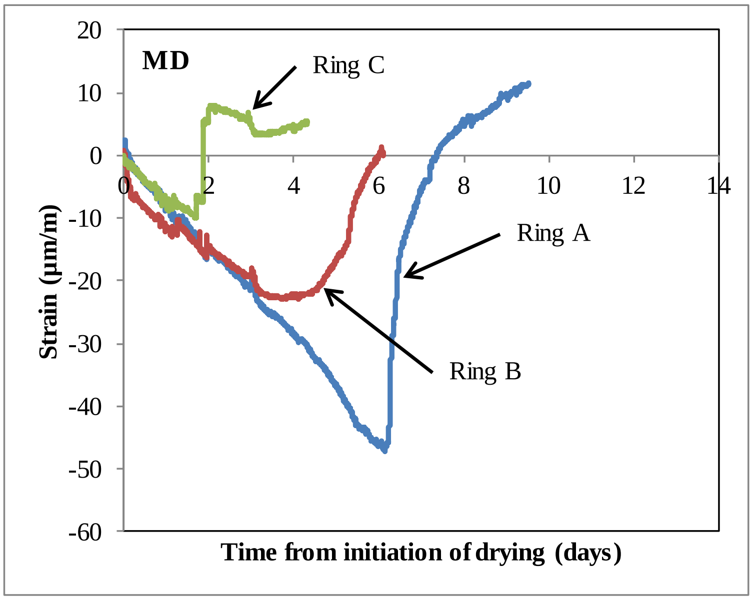
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	3.5	0.410	**Moderate High**
Ring B	7.1	0.305	
Ring C	8.4	0.197	
Average	**6.3**	**0.304**	

CPI	
Standard Cure	Mathed Cure
10.01	**7.15**

Mix ID:	**MD**	Cast date:	10/2/2013	Curing time (days):	**14**
Mix description:	ODOT HPC control mix with Medford coarse aggregate				
Fresh properties					
Batch size(cu ft):	3.5	w/cm:	0.37	Temperature (°C):	23.0
Slump (in):	2	Air content (%):	5.0	Unit weight (pcf):	142.9
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
27.1	2.91	32.0	30.7	3.33	28.4

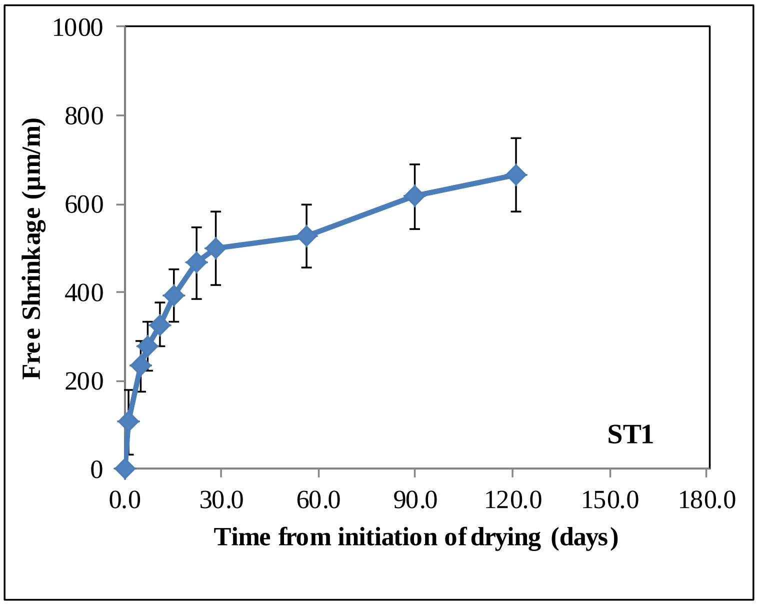


Time	Shrinkage (µm/m)	Std. Dev. (µm/m)
0	0	0.0
3	180	20.0
7	317	30.6
10	377	55.1
14	467	50.3
21	563	61.1
28	**610**	64.3
56	730	64.3
90	810	70.0
120	853	75.7
149	903	77.7
180	897	73.7

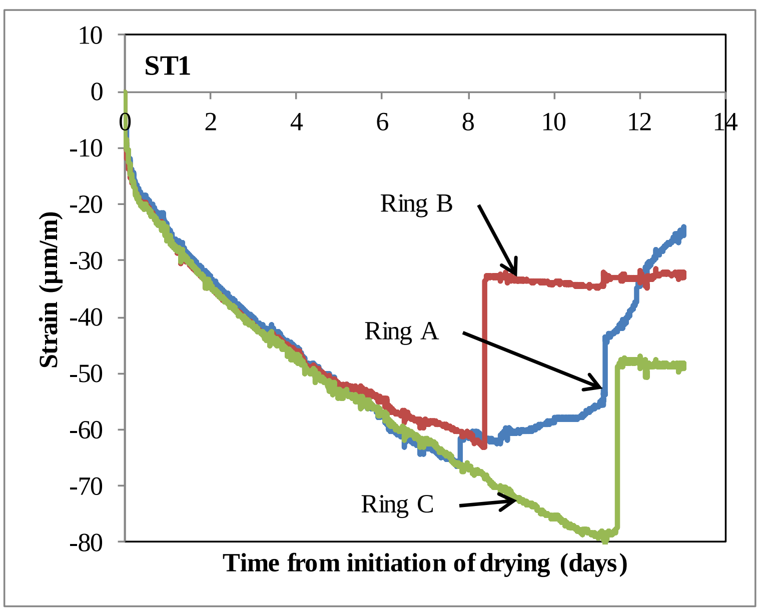


	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	6.3	0.279	**Moderate High**
Ring B	4.0	0.208	
Ring C	1.9	0.283	
Average	**4.1**	**0.257**	
CPI			
Standard Cure		Mathed Cure	
6.71		**5.20**	

Mix ID:	ST1	Cast date:	4/29/2013	Curing time (days):	3
Mix description:	ODOT HPC mix with Santosh (3/4") aggregate				
Fresh properties					
Batch size(cu ft):	3.4	w/cm:	0.37	Temperature (°C):	22.8
Slump (in):	3 1/4	Air content (%):	5.5	Unit weight (pcf):	144.0
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
34.6	3.92	31.1	31.4	3.70	26.8



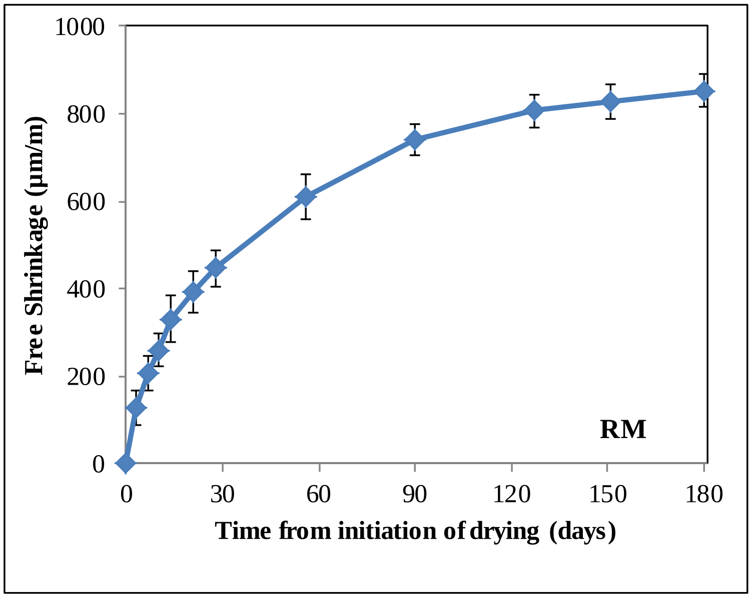
Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
1	107	72.3
5	233	58.6
7	277	55.1
11	327	50.3
15	393	58.6
22	467	80.8
28	**500**	83.3
56	527	72.3
90	617	73.7
121	667	83.3



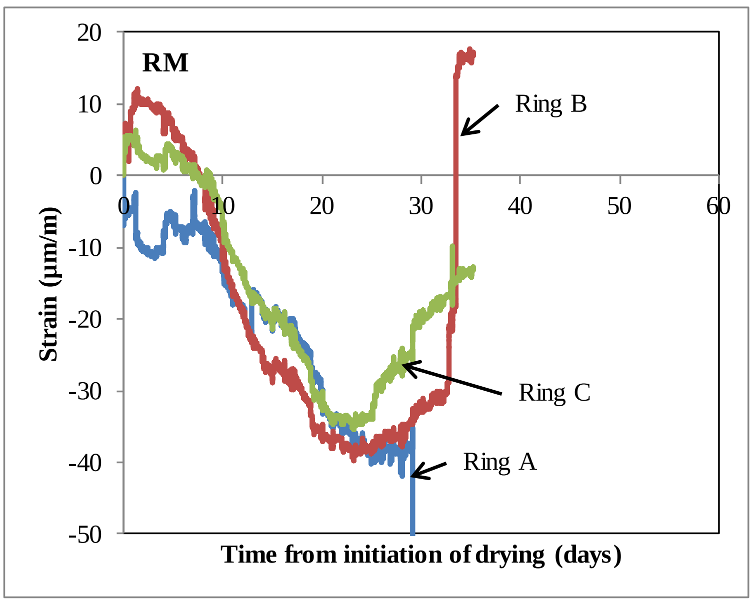
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	11.2	0.205	**Moderate High**
Ring B	8.4	0.243	
Ring C	11.4	0.227	
Average	**10.3**	**0.225**	

CPI	
Standard Cure	Mathed Cure
3.97	**3.62**

Mix ID:	**RM**	Cast date:	8/13/2012	Curing time (days):	**3**
Mix description:	Repair mortar, no coarse aggregate, mix according to manufacturer instruction				
Fresh properties					
Batch size(cu ft):	1.2	w/cm:	-	Temperature (°C):	25.0
Slump (in):	-	Air content (%):	-	Unit weight (pcf):	-
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
34.6	3.92	31.1	31.4	3.70	26.8



Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
3	127	40.4
7	207	40.4
10	260	36.1
14	331	52.2
21	393	49.3
28	**447**	41.6
56	610	52.9
90	740	36.1
127	807	37.9
151	827	40.4
180	853	37.9



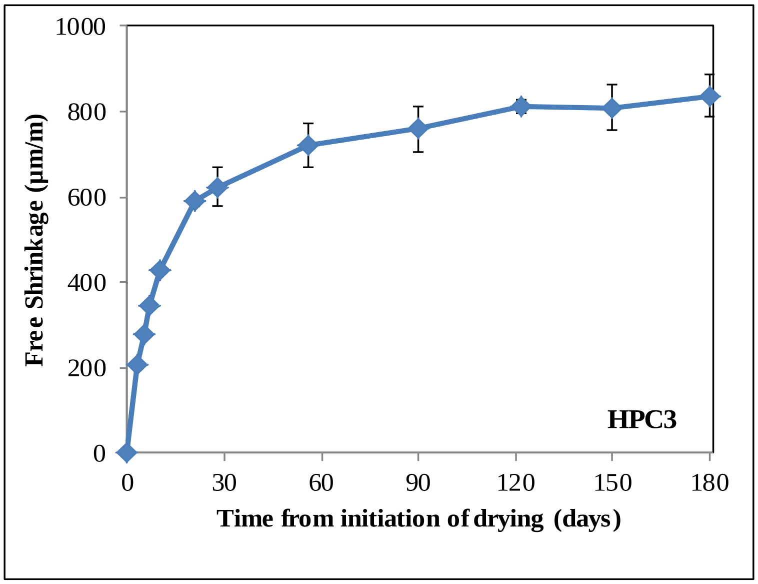
	ToC (days)	Stress Rate (Mpa/day)	Crack Risk Rating
Ring A	28.0	0.072	**Low**
Ring B	33.0	0.063	
Ring C	23.0	0.084	
Average	**28.0**	**0.073**	

.

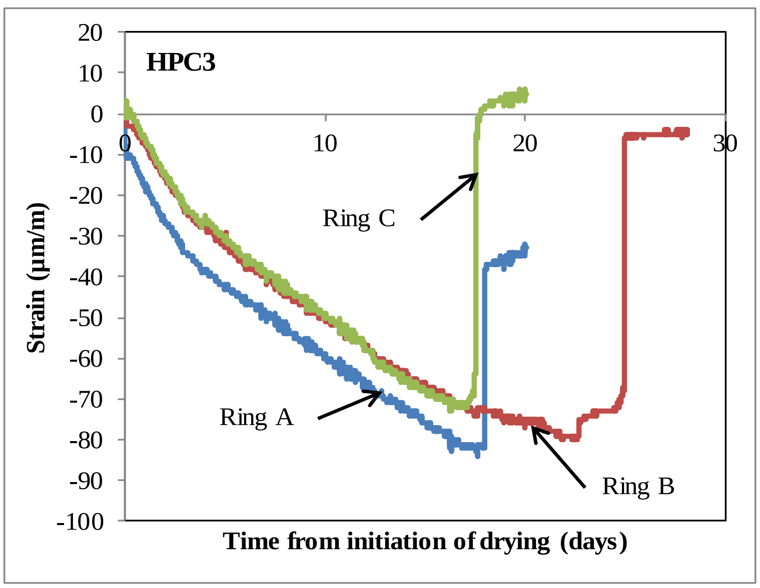
Standard Cure	Mathed Cure
-	**2.24**

APPENDIX B – AASHTO TESTING RESULTS SUMMARY

Mix ID:	HPC3	Cast date:	11/27/2012	Curing time (days):	3
Mix description:	ODOT HPC control mix, AASHTO ring				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	19.0
Slump (in):	3 3/4	Air content (%):	6.0	Unit weight (pcf):	142.8
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
29.0	3.58	32.3	27.0	2.98	27.2

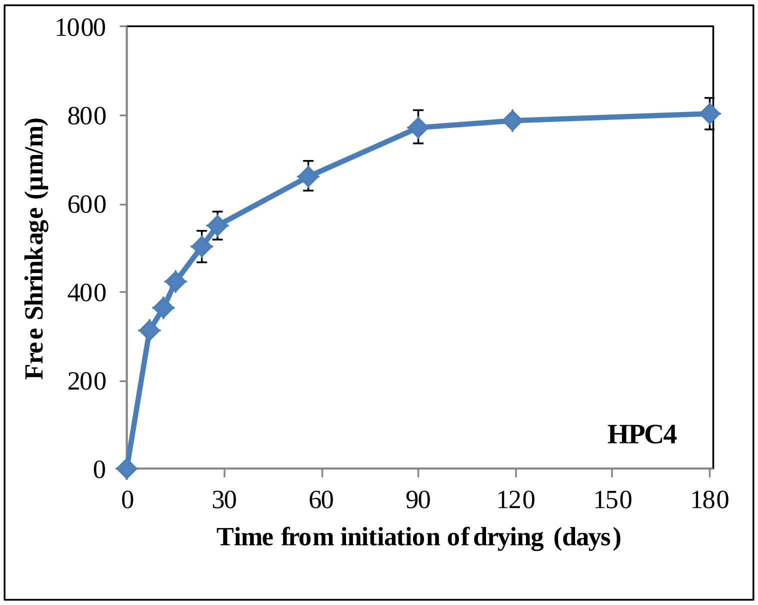


Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
3	207	5.8
5	277	5.8
7	347	5.8
10	427	5.8
21	590	10.0
28	**623**	46.2
56	720	52.0
90	760	52.9
122	813	15.3
150	810	52.9
180	837	49.3

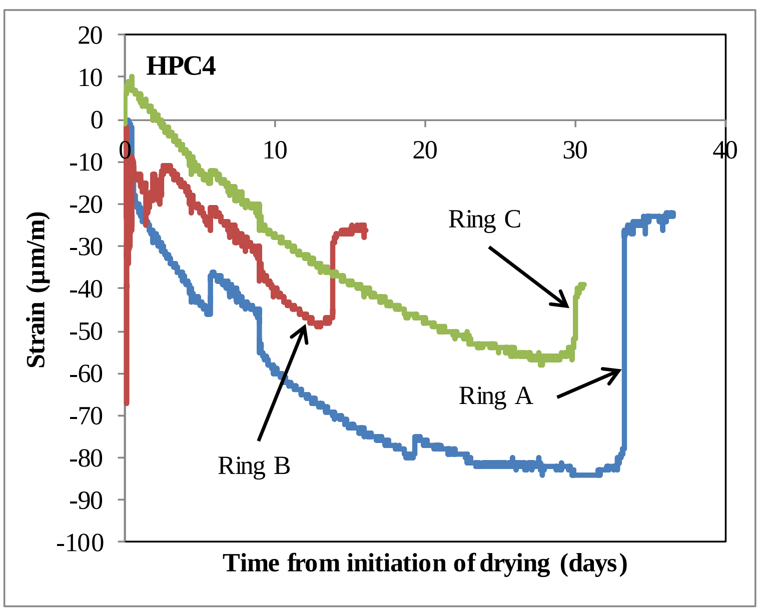


AASHTO	ToC (days)	Stress Rate (Mpa/day)
Ring A	18.0	0.153
Ring B	24.9	0.123
Ring C	17.5	0.131
Average	**28.0**	**0.136**

Mix ID:	**HPC4**	Cast date:	11/28/2012	Curing time (days):	**14**
Mix description:	ODOT HPC control mix, AASHTO ring				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	19.8
Slump (in):	4	Air content (%):	4.5	Unit weight (pcf):	145.3
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
39.7	3.99	35.5	42.1	4.18	29.8

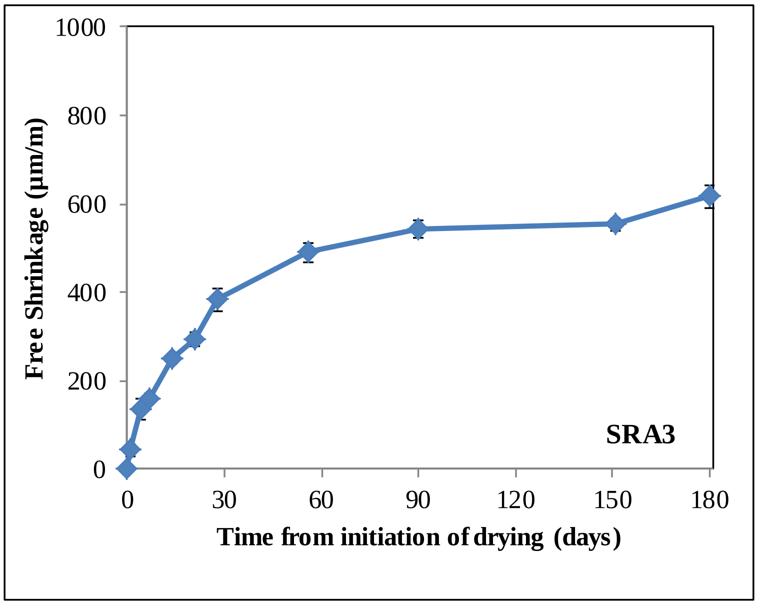


Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
7	313	5.8
11	366	5.8
15	423	5.5
23	503	35.1
28	**550**	32.1
56	663	32.1
90	773	37.9
119	790	5.8
180	804	34.6

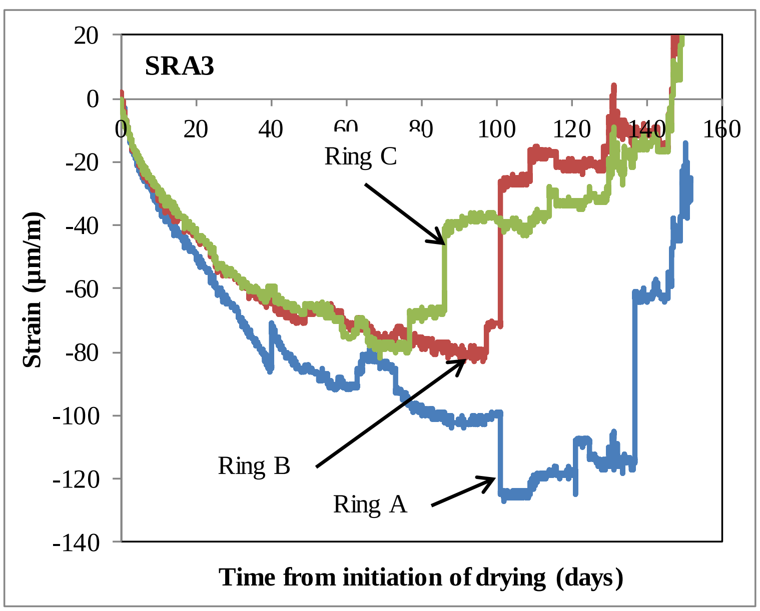


AASHTO	ToC (days)	Stress Rate (Mpa/day)
Ring A	33.1	0.107
Ring B	13.9	0.201
Ring C	30.0	0.148
Average	**25.6**	**0.152**

Mix ID:	SRA3	Cast date:	1/29/2013	Curing time (days):	3
Mix description:	ODOT HPC control mix + 2% SRA, AASHTO ring				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	20.8
Slump (in):	3 1/2	Air content (%):	4.0	Unit weight (pcf):	146.2
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
38.1	3.67	32.3	33.9	3.55	30.2

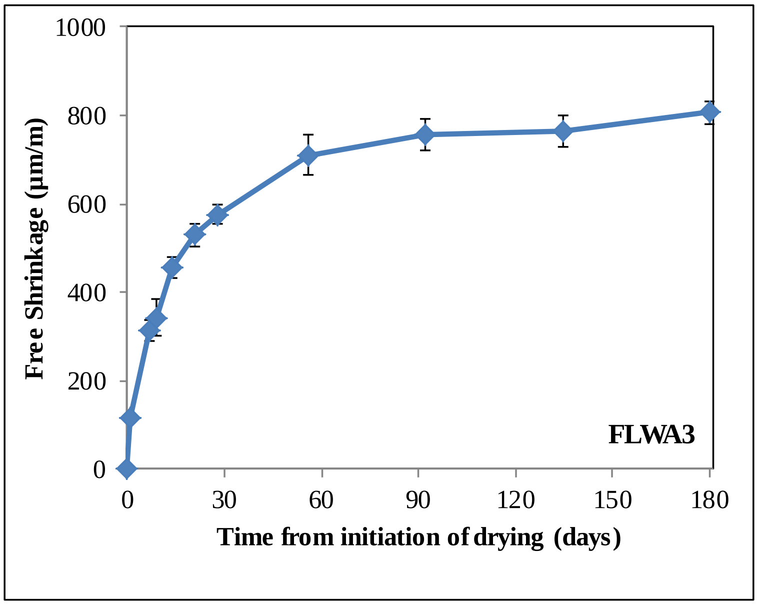


Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
1	43	15.3
4	137	23.1
7	160	10.0
14	250	10.0
21	293	15.3
28	**383**	25.2
56	490	20.8
90	543	20.8
151	553	15.3
180	617	25.2

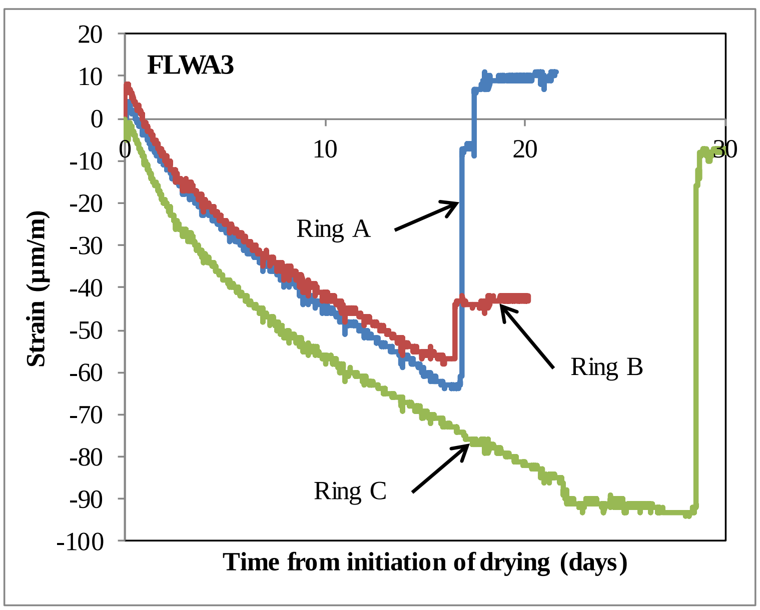


AASHTO	ToC (days)	Stress Rate (Mpa/day)
Ring A	135.0	0.034
Ring B	101.0	0.028
Ring C	86.7	0.037
Average	**107.0**	**0.033**

Mix ID:	**FLWA3**	Cast date:	2/1/2013	Curing time (days):	**3**
Mix description:	ODOT HPC mix with partial sand replacement with prewetted FLWA, AASHTO rings				
Fresh properties					
Batch size(cu ft):	4.0	w/cm:	0.37	Temperature (°C):	22.6
Slump (in):	3 1/4	Air content (%):	7.5	Unit weight (pcf):	135.6
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
36.3	3.67	28.5	31.3	3.16	25.2

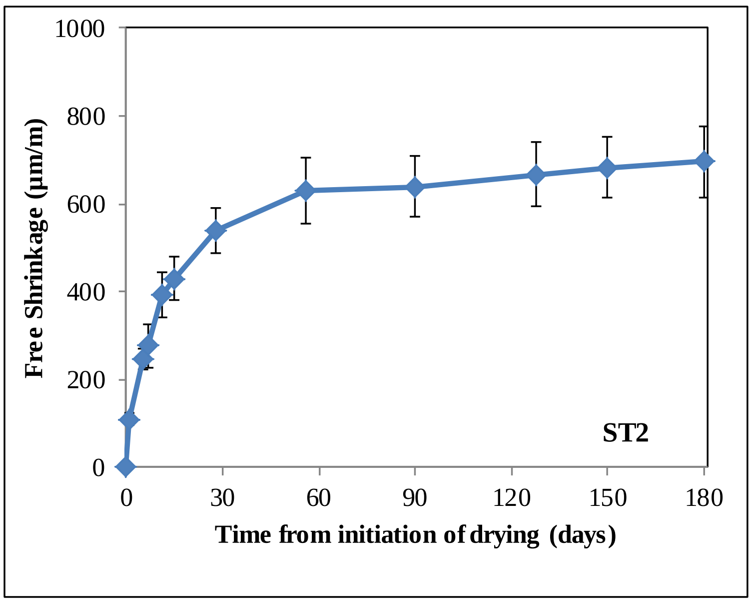


Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	0.0
1	117	5.8
7	313	25.2
9	343	40.4
14	457	23.1
21	530	26.5
28	**577**	23.1
56	710	45.1
92	757	35.1
135	763	35.1
180	807	25.2

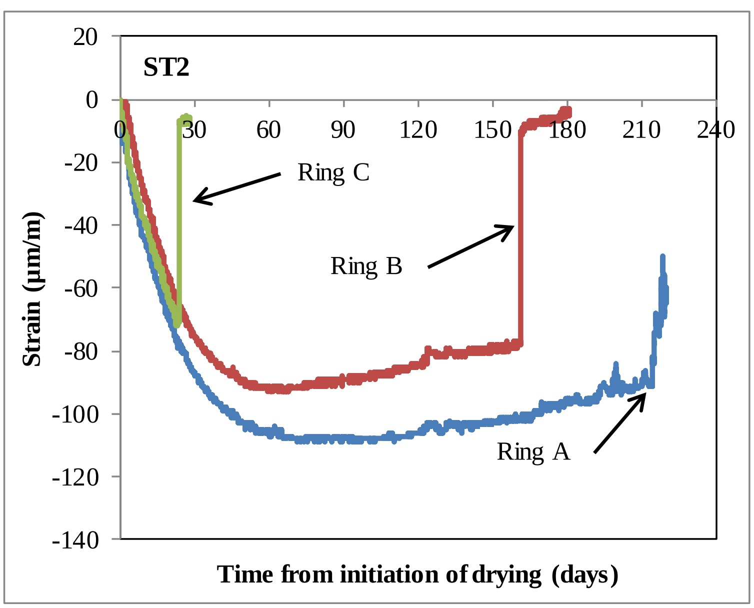


AASHTO	ToC (days)	Stress Rate (Mpa/day)
Ring A	16.8	0.159
Ring B	16.5	0.166
Ring C	28.7	0.141
Average	**20.7**	**0.155**

Mix ID:	**ST2**	Cast date:	11/21/2012	Curing time (days):	**3**
Mix description:	ODOT HPC mix with Santosh (1") aggregate, AASHTO rings				
Fresh properties					
Batch size(cu ft):	3.9	w/cm:	0.37	Temperature (°C):	19.6
Slump (in):	8 1/4	Air content (%):	7.5	Unit weight (pcf):	137.3
Hardened properties					
28 day standard cure			28 day matched cure		
fc (MPa)	ft (MPa)	E (GPa)	fc (MPa)	ft (MPa)	E (GPa)
27.8	3.25	29.7	232.0	2.15	25.6



Time	Shrinkage (μm/m)	Std. Dev. (μm/m)
0	0	10.0
1	110	15.3
5	247	23.1
7	277	49.3
11	393	52.9
15	430	49.3
28	**540**	52.0
56	630	73.7
90	640	70.0
128	667	73.7
150	683	68.1
180	697	81.4



AASHTO	ToC (days)	Stress Rate (Mpa/day)
Ring A	215.0	0.037
Ring B	162.0	0.031
Ring C	24.3	0.121
Average	**134.0**	**0.063**