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CREEP AND SHRINKAGE BEHAVIOR OF ULTRA HIGH PERFORMANCE CONCRETE UNDER
COMPRESSIVE LOADING WITH VARYING CURING REGIMES

By

Jason C. Flietstra

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

(Civil Engineering)

MICHIGAN TECHNOLOGICAL UNIVERSITY

2011

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This thesis, “Creep and Shrinkage Behavior of Ultra High Performance Concrete under Compressive Loading with Varying Curing Regimes,” is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN CIVIL ENGINEERING.

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Abstract

This Ultra High Performance Concrete research involves observing early-age creep and shrinkage under a compressive load throughout multiple thermal curing regimes. The goal was to mimic the conditions that would be expected of a precast/prestressing plant in the United States, where UHPC beams would be produced quickly to maximize a manufacturing plant's output. The practice of steam curing green concrete to accelerate compressive strengths for early release of the prestressing tendons was utilized (140°F [60°C], 95% RH, 14 hrs), in addition to the full thermal treatment (195°F [90°C], 95% RH, 48 hrs) while the specimens were under compressive loading. Past experimental studies on creep and shrinkage characteristics of UHPC have only looked at applying a creep load after the thermal treatment had been administered to the specimens, or on ambient cured specimens. However, this research looked at mimicking current U.S. precast/prestressed plant procedures, and thus characterized the creep and shrinkage characteristics of UHPC as it is thermally treated under a compressive load. Michigan Tech has three moveable creep frames to accommodate two loading criteria per frame of $0.2f'_{ci}$ and $0.6f'_{ci}$. Specimens were loaded in the creep frames and moved into a custom built curing chamber at different times, mimicking a precast plant producing several beams throughout the week and applying a thermal cure to all of the beams over the weekend. This thesis presents the effects of creep strain due to the varying curing regimes.

An ambient cure regime was used as a baseline for the comparison against the varying thermal curing regimes. In all cases of thermally cured specimens, the compressive

creep and shrinkage strains are accelerated to a maximum strain value, and remain consistent after the administration of the thermal cure. An average creep coefficient for specimens subjected to a thermal cure was found to be 1.12 and 0.78 for the high and low load levels, respectively.

Precast/pressed plants can expect that simultaneously thermally curing UHPC elements that are produced throughout the week does not impact the post-cure creep coefficient.

1 Introduction and Motivation

1.1 Introduction of Ultra High Performance Concrete (UHPC)

Today concrete is the most used man made resource on earth responsible for a \$35 billion per year revenue while employing over 2 million people in the United States alone (Lomborg 2001). Its history may be traced back all the way to the Egyptian pyramids, although the composition would be much different than what we use today. The Roman empires' widespread use of concrete helped preserve a history of architecture, and helped build some of the first metropolises with multistory buildings and aqueducts. The compressive strengths of Roman structures were similar to normal strength concrete (NSC) compressive strengths today, but the tensile strength of these structures were very weak and could only depend on the strength of the concrete bond to resist tensile forces (Robert 1986). It would not be until the 1850's when the newly discovered Portland cement and the use of reinforcing steel would be implemented in standard concrete construction practices producing reinforced concrete. Since then, most of the advances in concrete can be credited to the 20th century engineers.

The idea of prestressing concrete was introduced in the late 19th century and has been used by engineers to help modern day concrete structures increase both load carrying capacities and spans between supports, and reducing the amount of concrete material. However, it was not until the middle of the 20th century that prestressed

concrete was fully understood; which could explain early setbacks on prestress losses due to instantaneous events such as elastic shortening, friction loss and anchorage set, and the time-dependent losses due to strand relaxation, and concrete creep and shrinkage (Naaman 2004). Today prestressing applications can be seen in all areas of concrete construction, with new advances being considered. One such advancement being used in other areas of the world, but not fully understood in the U.S. is ultra-high performance concrete (UHPC) which can reach compressive strengths as high as 30 ksi after a thermal treatment.

UHPC was first developed in Europe in the 1990's and has since been an interesting material for research and use around the world (Nyland 2009). Use in the U.S. has been limited to a few applications in Iowa (Wapello County bridge), Michigan (slender columns in a cement silo), and Illinois (clinker silo long-span roof structure) primarily due to UHPC's high cost and lack of a design code. However, several countries have implemented design recommendations for UHPC including Australia (UNSW 2000), France (AFGC/SETRA 2002), and Japan (JSCE 2006), which can be used as a starting point for research in the U.S.

The advantages of UHPC go beyond the high compressive strengths previously mentioned. Impressive tensile strengths of 7 ksi are reached without the need for mild steel reinforcement. UHPC also exhibits advantageous durability properties such as low porosity, extremely low permeability, high ductility, resistance to leaching and corrosion, and after a thermal treatment, no additional shrinkage and very little creep

is observed (Graybeal 2005, Mission 2008, and Peuse 2008). These characteristics make UHPC a very unique building material, and one of particular interest in the precast/prestress industry. Several universities throughout the country including Michigan Tech, Georgia Tech, Virginia Tech, Iowa State, and Ohio University are currently conducting research studies on UHPC working toward a U.S. design code and standards for testing and designing with UHPC. This research will look at the early-age compressive creep and companion shrinkage of UHPC for use in the precast/prestress industry by mimicking standard practices currently being used on NSC, and high strength concrete (HSC) (up to 15 ksi). Previous research in this area only considered compressive creep effects of UHPC either after a thermal treatment was performed, or on ambient cured specimens. This research will look at the UHPC in compression at all stages before, during, and after the administration of a thermal cure, while keeping a constant compressive load on the UHPC specimens. Several curing regimes will be investigated such as delayed onset thermal cures, and the implantation of a pre-steam cure to accelerate the compressive strength prior to the application of a compressive load.

1.2 Objective

The objective of this research is to define the creep and shrinkage behavior of UHPC under a compressive load with varying onset thermal curing treatments. While previous research has measured creep and shrinkage strains on UHPC, the specimen strain measurements were only observed on ambient cured specimens, or after a recommended thermal cure. The goal of this research is to mimic procedures that

would be expected of a common precast/prestress plant in the U.S. As such, this research considered five unique curing regimes, where creep specimens were under a compressive load during a thermal cure.

1.3 Scope of Research

The curing regimes for this research differed from previous research at Michigan Tech. In addition to ambient cure conditions, a pre-steam thermal cure was implemented to accelerate the compressive strength of the UHPC prior to testing. Table 1.1 defines the curing regimes. The composition of all the mixed, cast and tested UHPC was completed with procedures similar to previous work at Michigan Technological University (Michigan Tech) (Kollmorgen 2004, Misson 2008, Peuse 2008, and Nyland 2009). To complete this research, seven batches of UHPC were required as seen in the test matrix in Table 1.2.

Loading of the test specimens was done once the specimens reached the recommended compressive strength for the release of prestress of 14 ksi. This

Table 1.1
Curing regimes defined

Abbreviation	Description of Curing Regime
AMC	Ambient cure for 70 hrs, then loaded in compression, continue ambient cure
SST	Ambient cure for 70 hrs, loaded, standard thermal cure applied
PST	Pre-steam cure for 14 hrs, loaded, standard thermal cure applied
PSD	Pre-steam cure for 14 hrs, loaded, ambient conditions for 72 hrs, standard thermal cure applied
PDD	Pre-steam cure for 14 hrs, loaded, ambient conditions for 11 days, standard thermal cure applied

required early-age compressive testing for both ambient and pre-steam cured specimens to locate the time, from batching, when specimens reached a compressive strength of 14 ksi. Using previous research for early-age compressive strength (Nyland 2009) and reproducing the strength gain studies helped determine an approximate time for creep loading to be applied on the UHPC specimens, simulating future U.S. precast/prestressed plant practice.

Nine 3.0-in diameter by 12.0-in. long cylinders were required for each curing regime. Three cylindrical specimens were loaded in compression at the high load level of $0.6f'_{ci}$ (8.4 ksi), and three specimens were loaded at the low load level of $0.2f'_{ci}$ (2.8 ksi). The final three specimens were used as companion shrinkage specimens and were subjected to the curing regimes, but not the load. Three specimens, 6.0-in. in length were tested to determine the compressive strength of the UHPC at the time of loading.

Twelve specimens were tested for each of the compressive strength gain studies to locate the target compressive strength of 14 ksi. These studies determined the age at which the creep specimens would be loaded in compression using an ambient cure time, and a pre-steam treatment to accelerate the compressive strength of the UHPC. The curing scenarios of the UHPC while undergoing a compressive creep load are listed in Table 1.1. Prior to compressive creep loading, specimens attained a compressive strength of 14 ksi by either an ambient cure or pre-steam cure. Once the specimens reach this compressive strength, standard dimensional measurements were recorded

and the specimens were subjected to the compressive creep loading. Once loaded in constant compression, specimens were left in the ambient cure condition and only removed from the ambient cure room to undergo the thermally treatment at varying times, which would best mimic precast production facilities.

Table 1.2
Experimental test matrix

Curing Regimes	Creep Monitoring				Shrinkage Monitoring		Compressive Strength	
	Compressive Stress @ Loading	Applied Stress Level	# of Cylinders	Size of Cylinders	# of Cylinders	Size of Cylinders	# of Cylinders	Size of Cylinders
AMC	14ksi	8.4 ksi 2.8ksi	3 3	3"x12"	3	3"x12"	4	3"x6"
SST	14ksi	8.4 ksi 2.8ksi	3 3	3"x12"	3	3"x12"	4	3"x6"
PST	14ksi	8.4 ksi 2.8ksi	3 3	3"x12"	3	3"x12"	4	3"x6"
PSD	14ksi	8.4 ksi 2.8ksi	3 3	3"x12"	3	3"x12"	4	3"x6"
PDD	14ksi	8.4 ksi 2.8ksi	3 3	3"x12"	3	3"x12"	4	3"x6"
Ambient Cure Compressive Strength Specimens							12	3"x6"
Pre-Steam Cure Compressive Strength Specimens							12	3"x6"

1.4 Outline of Report

The first two chapters of this report cover the background and development of UHPC, and the motivation for this research. Chapter 3 discusses the experimental plan, ASTM modifications, specimen preparation, testing procedures, and data acquisition. Chapters 4 and 5 present and discuss the data from the different curing regimes tested. The final chapter (6) cites conclusions of the research and offers recommendations for future work.

2 Background and Literature Review

2.1 Ultra High Performance Concrete

UHPC was introduced two decades ago as an advanced concrete material with enhanced mechanical and durability properties. Most UHPC research and applications have occurred outside of the United States. However since the late 1990's more research and studies have taken place at universities within the United States, including Michigan Tech, Georgia Tech, Iowa State, Ohio University, and Virginia Tech. Through the research at these institutions, UHPC has been examined and compared to findings outside of the U.S. In all cases, UHPC has been found to be a very durable material benefiting from high ductility and low porosity, making the material almost impermeable (Misson 2008). UHPC is also resistant to leaching and corrosion (Graybeal 2005). Once UHPC is thermally treated, virtually no shrinkage and limited creep has been observed (Graybeal 2006). Most impressively, however, is the high compressive strengths (30 ksi) and tensile strengths (7 ksi) observed after a thermal cure (Graybeal 2005).

UHPC is able to achieve these specific mechanical and durability properties by eliminating coarse aggregate, in order to optimize the particle packing of the constitutes. This compact cement matrix allows very few voids. Additionally, fiber reinforcement (2-10%) is introduced into the UHPC to provide tensile strength by the bridging of cracks in the UHPC. The lack of UHPC applications in the U.S. is due to the absences of a design code, although other counties have developed their own codes, in France (SETRA 2002), Japan (Japan 2006), and Australia (UNSW 2000). This literature

review will focus on compressive creep and companion shrinkage studies of UHPC, and recommended procedures for testing UHPC.

2.1.1 Primary Constitutes

UHPC shares many of the same constitutes that are used in NSC, however the proportioning of constitutes between the two materials differ. To optimize the packing abilities of UHPC, materials are selected based on the size and shapes of each constitute; this tightly packed cement matrix yields the unique mechanical and durability properties of UHPC. The UHPC used in this research was the brand Ductal[®] BSI 1000 marketed by Lafarge North America, and is distributed in a premix bag with the proper proportions of constitutes. The addition of water, superplasticizer, and steel fibers are added during mixing at predetermined times throughout the mixing procedure. Table 2.1 provides a breakdown of the typical composition of Ductal.

2.1.2 Background of Material Properties

UHPC exhibits impressive mechanical properties, which make it an attractive building material for several precast/prestressed applications. The manufacturer provides

Table 2.1
Ductal composition (Lafarge NA 2009)

Constitute	Proportion (lb/yd ³)	Percent by Weight
<i>Sand</i>	1719	41.1
<i>Cement</i>	1197	28.6
<i>Silica Fume</i>	388	9.3
<i>Ground Quartz</i>	354	8.5
<i>Metallic Fibers</i> <i>(8x10⁻³ -in dia. by 0.5-in long)</i>	270	6.4
<i>Water</i>	236	5.6
<i>Superplasticizer</i>	22	0.5

Table 2.2
Manufacturer's material properties (Lafarge NA 2009)

Mechanical Property	Range
Compressive Strength	23,000 - 33,000 psi
Tensile Strength	4,000 - 7,200 psi
Modulus of Elasticity	8 - 8×10^6 psi
Post Cure Shrinkage	< 10 $\mu\epsilon$
Creep Coefficient (with $w/c = 0.2$)	0.2 - 0.5

typical mechanical properties of this UHPC, material properties of interest can be seen in Table 2.2. Working towards new U.S. design standards for UHPC requires the repetition of results of new testing procedures to better understand the mechanical properties. Research at several U.S. universities, along with a Federal Highway Administration report released in 2006 (Graybeal 2006) provides several studies of UHPC's mechanical properties. The purpose of this thesis is to provide experimental results and conclusions of UHPC's compressive creep and companion shrinkage properties, to better understand the effects of creep for UHPC undergoing a thermal cure, while subjected to a compressive load.

2.1.3 Typical Curing Methods

UHPC is thought to "lock in" its mechanical and durability properties through a thermal cure occurring sometime after the UHPC is stripped of its molds. Different thermal curing treatments will affect the unique properties of the UHPC differently, including the compressive strength and the creep and shrinkage response. The curing regime necessary to reach the mechanical properties mentioned in Table 2.2 involves a 48-hour thermal cure at a temperature of 194°F (90°C), while holding a relative humidity at 95%. This curing method is most common among U.S. based research, and

will be applied to the UHPC specimens in this research known as the “standard thermal cure.”

Loukili et al. (1998) showed that thermal treatment of reactive powder concrete (RPC), developed by the Scientific Division of Bouygues, provided benefits in both shrinkage and creep of the RPC. When the RPC was not thermally treated, the RPC had shrinkage of 58% and 2 to 3 times the creep of high performance concrete was observed. During the standard thermal cure, autogenous shrinkage can be eliminated, due to an increase in cement hydration reactions which consume the free water within the cementitious matrix. The standard thermal cure can also reduce the creep of concrete specimens by complete drying of the concrete. Loukili et al. (1998) observed that by having the complete drying of the concrete causes the collapse of interlayer space within the C-S-H hydration product leading to significant reduction in creep.

Ambient curing of UHPC would typically be seen in cast-in-place applications, where applying a thermal treatment is not possible. Ambient conditions will vary with different field applications. In this research, this type of curing condition will be referred to as “ambient cure,” and conditions were held at constant laboratory conditions with a temperature range of $73.5^{\circ}\text{F} \pm 3.5^{\circ}\text{F}$, and relative humidity range of $50\% \pm 4\%$, which is the ASTM C157 standard range for measuring length change in hardened cement (ASTM 2010). With this ambient cure condition, the UHPC has yet to lock in all of the mechanical and durability properties as seen with a thermal cure.

Graybeal (2005) experimented with lower temperature thermal curing which was termed a “tempered cure.” In many precast/prestress plants, standard U.S. practice

is to apply a steam treatment to accelerate the curing of the concrete, in order to clear the concrete casting beds quickly to produce more precast elements. Because mimicking what would be expected of precast/prestressed plant is the objective of this research, a “pre-steam cure” was implemented as a curing method to accelerate the early-age compressive strength of UHPC. The pre-steam cure follows Graybeal’s tempered cure procedures, which used a temperature of 140°F (60°C) at a relative humidity of 95%, and falls into the range of steam curing used by U.S. precast/prestressed plants.

A curing process which delays the onset of thermal curing was implemented by Graybeal (2005) and Peuse (2008). The delay allowed for more ambient curing time between the casting of the UHPC and the start of the thermal treatment process. Their research each showed that by delaying the thermal treatment no noticeable changes in compressive strength of thermally treated UHPC and the delayed thermally treated UHPC was observed. In the research reported herein, the UHPC specimens were subjected to a continuous compressive load before undergoing a standard thermal cure. By delaying the onset of the standard thermal cure, significant creep and shrinkage of the specimens was expected. Other than the manufacturer’s thermal treatment curing method, all additional curing methods investigated in this study are scenarios with realistic curing conditions for UHPC field applications.

2.2 Compressive Creep and Unrestrained ‘Free’ Shrinkage

Concrete undergoes three time dependent volumetric changes, which include shrinkage, compressive and tensile creep, and thermal expansion or contraction (Wight and MacGergor 2009). These volumetric changes cause internal stresses that

can lead to cracking or deflections affecting the serviceability of the concrete structure. This report focuses on the volumetric changes of compressive creep on UHPC, while accounting for the unrestrained shrinkage which will occur during the hardening and drying of the UHPC.

Drying shrinkage is caused by the loss of surface water particles that have been absorbed by the concrete. In typical normal strength concrete (NSC) structures, drying shrinkage due to unabsorbed free surface water particles will have little effect on the overall shrinkage of the specimen. Shrinkage only occurs in the hardened cement paste which bonds the aggregates together (Wight and MacGregor 2009). Therefore large cement to aggregate ratio would result in greater shrinkage in the specimen. More finely ground cement leads to larger cement surface area resulting in more absorbed water to be lost, leading to more shrinkage. UHPC differs from NSC in both cement content and water/cement (w/c) ratio. UHPC has a much higher fraction of finely ground cement than NSC with a lower water/cement ratio. Due to the low w/c ratio of UHPC, much of the cement particles will remain unhydrated in the cementitious matrix (Loukili et al. 1998). These unhydrated cement particles become fillers in the granular matrix which possess the ability for UHPC to “self-heal” when small cracks occur, which provides UHPC with a future hydration potential (Loukili et al. 1998). Mehta and Montiero (2006) observed that concretes with high cement content must also consider autogenous shrinkage. Autogenous shrinkage is also known as self-desiccation, which occurs during the hydration process resulting in a deformation of the cement paste (Mehta and Montiero 2006). When unrestrained shrinkage is referred to in this report, it will include the combination of drying shrinkage and autogenous shrinkage.

Creep is the tendency for a material to slowly deform permanently under the influence of stresses. When loaded in compression, concrete develops an instantaneous elastic strain (Wight and MacGergor 2009). If the compressive load is sustained on the concrete over a duration of time, creep strains develop due to the absorbed water layers becoming thinner within the concrete (Wight and MacGergor 2009). The rate of creep occurs more rapidly initially after the load is applied and tends to decrease over time. Wight and MacGergor (2009) note that new bonds between the thinner absorbed water layers occur which result in a permanent deformation once the load is removed. The term *creep coefficient*, Φ is termed to the ratio of creep strain (after a long time) to elastic strain, ϵ_c/ϵ_i . An illustration detailing initial elastic strain, with creep and shrinkage strain development in NSC versus increasing time, and resulting from load application/removal is included as Figure 2.1.

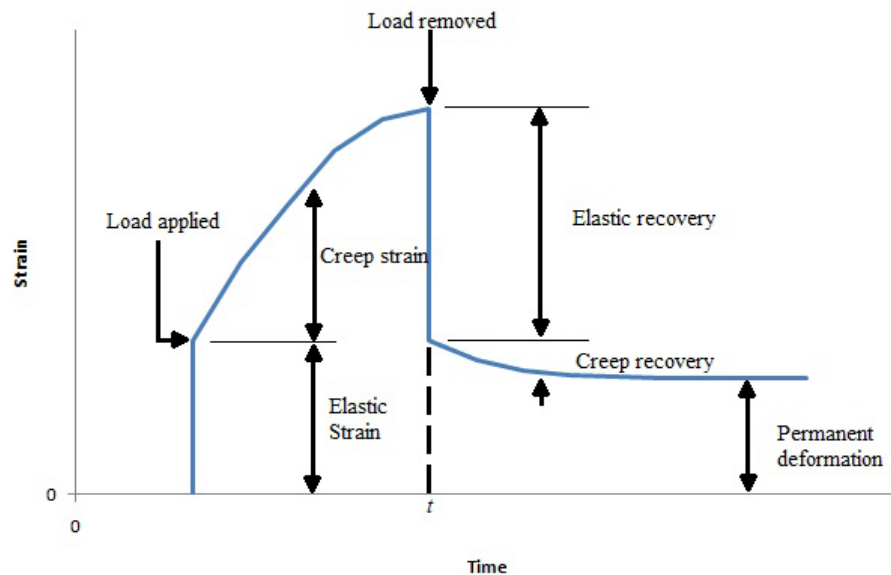


Figure 2.1 Elastic and creep strains due to loading (Adapted from Wight and MacGregor 2009)

The creep coefficient is affected by several conditions such as the ratio of sustained load to the concrete compressive strength, age at which the concrete was loaded, concrete element dimensions, relative humidity, and the composition of the concrete (Nawy, 2009). It is important to note that greater creep is observed in high fraction cement concretes, typical of UHPC. This higher creep is due to the lower amount of aggregate in the concrete because, like shrinkage, only the hydrated concrete paste will creep (Wight and MacGregor 2009). The creep strain will eventually approach an asymptotic maximum value gradually increasing over time with sustained loading, resulting in a value for *ultimate creep strain* (Naaman 2004).

2.2.1 ASTM Standards for Nominal Strength Concrete

The American Society for Testing and Materials, ASTM, provides engineers with standard practices for proportioning, mixing, placing, and testing NSC. The importance of having ASTM standards in concrete construction allows for consistent testing of material properties used to develop codes that engineers rely on. Engineers are able to have confidence in designs knowing that design relationships were developed, justifying factors of safety and design recommendations in such codes and guidelines as ACI 318 and the PCI Design Handbook. For this research in compressive creep and shrinkage testing, it is important to understand the standard practices for testing NSC. However, UHPC often requires modifications for applicability and there are currently no ASTM standards for testing the behavior of UHPC.

The current standard test method in the U.S. for unrestrained shrinkage is “Length Change of Hardened Hydraulic-Cement Mortar and Concrete” ASTM C157 (ASTM 2010). This standard calls for the casting of a minimum of 3 prismatic specimens measuring

3.0-in. by 3.0-in. with a minimum length of 11 ¼-in. Gage studs are cast into the ends of the specimens to monitor dimensional length changes with the use of a comparator and a reference bar (ASTM 2010).

The current standard test method in the U.S. for Creep of Concrete in Compression is ASTM C512 (ASTM 2010). This standard calls for the construction of a creep frame that is able to maintain a constant load during the dimensional changes of the test specimens. A permanently installed hydraulic jack and load cell must be able to measure the load to the nearest 2% of the total applied load, and the load can be maintained with the use of springs (ASTM 2010). However when springs are used, in order to ensure uniform loading of the specimens, the use of a spherical bearing assembly must also be used (ASTM 2010).

For creep testing, test specimens are required to be cylindrical with a diameter of 6.0-in. $\pm 1/16$ -in. and a length of at least 11 ½-in. The ends of the specimens must meet plane and parallel requirements and can be cast vertically or horizontally with horizontal mold requiring instrumentation of an internal strain measuring device. The specimens are permitted to be in direct contact with the steel bearing plates when the specimen length is “at least equal to the gage length of the strain-measuring apparatus plus the diameter of the specimen” (ASTM 2010). Per ASTM C512, no fewer than 6 specimens shall be cast and tested for compressive creep, two for creep loading, two specimens to undergo companion shrinkage monitoring, and the final two specimens to be tested for compressive strength. The maximum allowable compressive creep stress allowed for creep monitoring is 40% of the compressive strength at time of loading. A complete creep behavior study for concrete specimens

requires that specimens be loaded at the ages of 2, 7, 28, 90 days, and 1 year (ASTM 2010). Both creep and companion shrinkage dimension changes are measured and recorded. Measurements were taken immediately before compressive loading, and after the load was applied. Further measurements were recorded at 2 to 6 hours after loading, then daily for one week, then weekly for one month, then monthly until the duration of 1 year (ASTM 2010).

2.2.2 UHPC Recommendations for Creep and Shrinkage

No current design standard for UHPC exists in the U.S., and as such no U.S. design recommendations for compressive creep and shrinkage can be made. However, outside the U.S. several design recommendations have been produced. These recommendations come out of France, Japan, and Australia. Understanding how these recommendations accounted for the unique mechanical and durability properties of UHPC will help to define a preliminary U.S. testing procedure that can follow the ASTM guidelines for NSC as closely as possible.

2.2.2.1 French recommendation

Interim recommendations for Ultra High Performance Fibre-Reinforced Concretes (UHPFRC) were released in 2002 by the Association Française de Génie Civil (AFGC)/Service d'études techniques des routes et autoroutes (SETRA) (AFGC/SETRA 2002). This document included recommendations for shrinkage and creep, and are outlined in Annex 4 of the AFGC/SETRA 2002 interim recommendations citing the test results found by Loukili et al. (1998), the Sablons Technical Centre, and the Centre Expérimental de recherches et d'études du Bâtiment et des Travaux Publics (CEBTP). When the Lafarge Ductal® brand of UHPC is used without applying a standard steam

treatment, the AFGC/SETRA recommends a total shrinkage strain of 550 microstrain and a creep coefficient of 0.8. After a standard steam cure is administered, no further shrinkage strains are observed and a creep coefficient of 0.2 is recommended; where the standard steam cure followed the Lafarge recommended procedure outlined in section 2.1.3 (AFGC/SETRA 2002).

Loukili et al. (1998) concluded that no autogenous shrinkage occurs in UHPFRC after a standard thermal cure, and that autogenous shrinkage will increase with increasing water to cementitious material (w/c) ratios (AFGC/SETRA 2002). Loukili et al. (1998) observed autogenous shrinkage strains of 250 and 350 microstrain with w/c ratios of 0.09 and 0.15, respectively. A total shrinkage strain of 550 microstrain was observed for a w/c ranging from 0.17-0.20 when specimens were subjected to a standard thermal cure (AFGC/SETRA 2002). UHPFRC specimens not subjected to a thermal cure were observed by Loukili et al. to obtain a maximum shrinkage strain of 525 microstrain. The expression in equation 2.1 developed by Loukili et al. models the total autogenous shrinkage for ambient cured specimens. Equation 2.1 was tested and verified by the Sablons Technical Centre and the CEBTP in the AFGC/SETRA recommendations.

2.1

$$\varepsilon_{rt}(t) = 525 \left[\frac{-2.5}{\sqrt{t-0.5}} \right]$$

Where:

$\varepsilon_{rt}(t)$ = autogenous shrinkage of UHPFRC without a standard thermal cure.
 t = elapsed time from casting in days.

The AFGC/SETRA recommendation cites the observations of Loukili et al. that once a standard thermal cure has been administered to the UHPFRC, creep is significantly reduced. Table 2.3 shows the findings of Loukili et al. based on UHPFRC under a compressive load without heat treatment. Loukili et al. observed a delayed creep response of the ambient cured specimens when compared to the rapid creep response observed with specimens subjected to a standard thermal cure, and later loading of the specimens resulted in lower specific creep and creep coefficients (final creep strain divided by the initial elastic creep) (AFGC/SETRA 2002). The specific creep calculation in Table 2.3 refers to the creep coefficient divided by the modulus of elasticity at infinity of the UHPFRC. Loukili et al. developed the expression for basic specific creep of UHPFRC as seen in equation 2.2.

Table 2.3
Creep under compressive load without a standard thermal cure (Loukili et al. 1998,
AFGC/SETRA 2002)

Date of loading (days)	Specific creep at infinity ($\mu\epsilon$ /ksi)	Creep Coefficient
1	323.4	2.27
4	256.6	1.80
7	224.1	1.57
28	153.1	1.08

The AFGC/SETRA recommendations for creep response in UHPFRC without a standard thermal cure cite equation 2.2 to be used to calculate basic specific creep at any specific time in days from applied compressive loading, as verified by Loukili et al. the Sablons Technical Centre and the CEBTP.

2.2

$$\epsilon_s = k(t_o) * f(t - t_o) + h(t_o)$$

Where:

2.3

$$k(t_0) = 19\sqrt{\frac{0.1}{t_0 - 2.65}}$$

2.4

$$f(t - t_0) = \frac{\sqrt{\frac{t - t_0}{3t_0 - 5}}}{\sqrt{\frac{t - t_0}{3t_0 - 5}} + 1}$$

2.5

$$h(t_0) = 18\sqrt{\frac{0.2}{t_0 + 1.2}}$$

ε_s = basic specific creep in ambient cured UHPFRC
 t = elapsed time from casting in days
 t_0 = time at loading in days

For UHPFRC specimens subjected to a standard thermal cure, the AFGC/SETRA recommendation cites the results of the Sablons Technical Centre and the CEBTP. Equation 2.6 provides an expression for total strain following a standard thermal cure.

2.6

$$\varepsilon(t) = \frac{\sigma}{E_i} [1 + K_{fl} * f(t - t_0)]$$

Where:

$\varepsilon(t)$ = total strain in the UHPFRC (μ)
 K_{fl} = creep coefficient (0.30)
 σ = creep stress applied
 E_i = modulus of elasticity of the UHPFRC

$$f(t - t_0) = \frac{(t - t_0)^{0.6}}{(t - t_0)^{0.6} + 10}$$

2.7

t = elapsed time from casting in days
 t_0 = time at loading in days

2.2.2.2 Japanese Recommendation

The Japanese Society of Civil Engineers (JSCE) released a draft version of the *Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures* in 2006. The distribution of materials used in UFC (UHPC) referenced in the Japanese recommendations is included in Table 2.4. The JSCE found that shrinkage of the UFC is primarily due to autogenous shrinkage with shrinkage strains reaching approximately 450 microstrain during the heat cure and an additional 50 microstrain following the heat cure (JSCE 2006). The JSCE heat cure is similar to the Lafarge recommended 194°F (90°C) for 48 hours at 95% relative humidity. Prior to the heat cure, the UFC is subjected to an initial cure of 104°F (40°C) until a compressive strength of 5800-7250 psi is attained. Ramp up temperature rates for the heat cure increase 59°F (15°C) per hour until the target temperature of 194°F (90°C) is reached, and the cool down is accomplished by ambient air cooling (JSCE 2006). When shrinkage specimens were not subjected to the heat cure, the JSCE recommends a total shrinkage strain of 550 microstrain. The JSCE provides recommended shrinkage strains, as seen in Table 2.5 for UFC batched and cast with the JSCE recommendations

Table 2.4
Mix proportions of UFC (UHPC) using standard mixed ingredients (Adapted from JSCE 2006)

Constitute	weight (lb/ft ³)	% by weight
<i>Low-heat Portland Cement</i>		33-45
<i>Aggregate</i>	140.7	28-42
<i>Intermediate materials</i>		10-24
<i>Silica fume</i>		7-11
Water	11.24	6.9
Steel fibers (7.8x10-3in-dia x 0.6in-length)	9.80	6.0
High-range water reducing agent	1.50	0.9

Table 2.5
Typical shrinkage strain values (10^{-6}) of UFC (UHPC) (Adapted from JSCE 2006)

Standard Heat curing	Age of UFC (days)				
	< 3	4-7	28	90	365
	50	30	0		

if tests are not performed to calculate the shrinkage strain. The JSCE performed creep testing on UFC specimens measuring 4-in. diameter and 8-in. in length under a compressive level of approximately 14.5 ksi at a UFC age of 7 days after casting. No specific load level was provided by the JSCE. Specimens were of the specific ingredients and batched in the procedures recommended by the JSCE. The tests were monitored for one year and produced a creep coefficient of 0.33 (JSCE 2006). When no creep testing can be performed, the JSCE recommends that a conservative creep coefficient of 0.4 be used when UFC is batched, cast, and subjected to the standard heat cure as outlined in the JSCE recommendations. When specimens are not subjected to a standard heat cure, the JSCE references the AFGC/SETRA creep coefficient of 1.2 as the final creep factor.

2.2.2.3 Australian Recommendation

The N Gowripalan and R I Gilbert School of Civil and Environmental Engineering at the University of South Wales in Australia have provided recommendations for design and testing UHPC beams. In January 2000, the university released *Design Guidelines for RPC Prestressed Concrete Beams*, with testing procedures using the Ductal® brand UHPC developed by Bouygues, S.A., of Paris, France (UNSW 2000). However, only short summaries of the creep and shrinkage response design guidelines are provided based on other research.

The UNSW design guidelines note that shrinkage occurring in UHPC differs from the drying shrinkage as seen in NSC. The shrinkage in the UHPC is due to chemical reactions within the concrete. Whether the UHPC is ambient cured or steam cured at 194°F (90°C) for 48 hours, UHPC will experience a shrinkage strain of approximately 500µε. The steam cured specimens experience an accelerated strain with all of the strain occurring during the steam cure with no subsequent shrinkage strain occurring after the steam cure. Ambient cured specimens were found to have an increase in shrinkage strain up to 28 days with almost no subsequent shrinkage after 28 days (UNSW 2000).

As with NSC, the creep in UHPC depends on the age at first loading and the duration of the applied stress. The final *creep coefficient*, Φ , in UHPC also depends on the temperature and duration of the steam cure. Specimens loaded at 28 days after being subjected to a steam cure treatment obtained a creep coefficient of 0.3. If the UHPC is not steam cured, then the creep coefficient can be as high as 1.2 for specimens loaded at 28 days and 1.80 for specimens loaded at 4 days (UNSW 2000). Table 2.6 details the UNSW findings of final creep coefficient with loading at 4, and 28 days with and without the use of a steam cure.

Table 2.6
Final creep coefficient at time of loading (UNSW, 2000)

Time of Loading	Final Creep Coefficient	
	Without Steam Cure	With Steam Cure
4 days	1.8	0.5
28 days	1.2	0.3

2.2.3 Additional Studies

In addition to the recommendations discussed in 2.2.2, further studies have occurred. At the University of Karlsruhe in Karlsruhe Germany, Burkart and Müller currently have a project underway investigating the creep and shrinkage characteristics of UHPC. The creep and shrinkage studies involve two reference concretes, a fine grain (M2Q) and a coarse grain concrete, both developed by the University of Karlsruhe. These reference concretes were examined and compared to the German DIN 1045 standard for NSC. Information presented herein discuss only the results of the M2Q concrete (constitutes provided in Table 2.7) tested by Burkart and Müller, as it most closely matches the UHPC considered in this study. Specimens were cast and allowed to cure in water for 6 days at a constant temperature of 68°F (20°C). After, the water cure specimens were placed in an ambient cure room held at 68°F (20°C) and 65% relative humidity until testing (Burkart and Müller 2008).

Specimens used to determine compressive strength and modulus of elasticity had identical dimensions of approximately 6 inch diameter (150mm) by approximately 12 inch length (300mm). Burkart and Müller demolded the specimens 24 hours from Table 2.8 provides the M2Q compressive strength and modulus of elasticity with respect of the age of the specimen. However, specimens tested at 1 and 3 days from demolding were only subjected to 1 and 3 days of the water cure respectively.

Burkart and Müller conducted shrinkage testing on M2Q specimens with varying dimensions and sealed or unsealed characteristics. Specimens varied in diameter from 3 inches (75mm), 4 inches (100mm), and 6 inches (150mm). All specimens monitored

Table 2.7
Composition of the reference concrete M2Q (Adapted from Burkart and Müller 2009)

Constituents	M2Q (lb/ft ³)
Quartz sand, H33 0.125/0.5 mm	60.9
Cement, CEM I 52.5 R-HS/NA	51.9
Quartz powder, Millisil W3	12.9
Steel Fibers, 1/d = 9/0.15 mm/mm (2.5 Vol.-%)	12.0
Water	10.4
Microsilica	8.4
Superplasticizer	2.1

Table 2.8
Mean values for compressive stress and modulus of elasticity of M2Q concrete (Adapted from Burkart and Müller 2008)

Age at testing (days)	Compressive Stress, f'_c (ksi)	Modulus of Elasticity, E (ksi)
1	7.40	4.48
3	14.65	5.86
28	24.08	6.92
120	26.98	8.01
180	28.14	8.01

for shrinkage maintained a diameter to height ratio of 1:3. Unsealed specimens allowed evaporation of moisture resulting in drying shrinkage, and sealed specimens were subjected to the application of butylcaoutchouc coated aluminum tape; which would restrict the evaporation of surface moisture from the specimens (Burkart and Müller 2008). All shrinkage specimens were stored in a temperature controlled room maintained at 68°F (20°C) and 65% relative humidity.

Burkart and Müller compared the results of their M2Q shrinkage specimens for varying specimen sizes and storage conditions with a predicted equation for shrinkage in the German DIM 1045 standard, which is not verified for UHPC. Both the sealed and unsealed shrinkage specimens, when subjected to the same curing conditions,

experienced similar shrinkage strains approaching $320\mu\epsilon$ after 200 days of measurements had passed (Burkart and Müller 2009). This observation, when compared to the DIM 1045 predicted equation, led Burkart and Müller to conclude that the autogenous shrinkage is significantly underestimated, and the drying shrinkage component is overestimated in the M2Q concrete (Burkart and Müller 2009). Burkart and Müller were also able to conclude that the specimen size has negligible influence on drying shrinkage but does have an effect on delaying diffusion processes which in turn affects the time development of the drying and autogenous shrinkage (Burkart and Müller 2009). Further experimentation is expected to distinguish between shrinkage deformation scatter and moisture loss. For the shrinkage strain in specimens with varying diameter sizes, all specimens appeared to be approaching an asymptotic shrinkage strain of $300\mu\epsilon$ after 200 days of measurements.

Burkart and Müller conducted compressive creep testing on M2Q specimens with varying age and loading stress and compared to the German DIM 1045 standard for NSC. The applied loading levels used by Burkart and Müller included a high level compressive stress of 60% of the compressive strength at loading, $0.6f'_{ci}$, and a low level compressive stress of 30% the compressive strength at loading, $0.3f'_{ci}$. All creep specimens (other than specimens loaded one day after demolding) were subjected to a thermal cure for 48 hours, and stored in an ambient controlled climate of 68°F (20°C) and 65% relative humidity until time of testing. Burkart and Müller were able to observe that “the magnitude of creep significantly decreased with the increasing concrete age.” In the creep experiments observed in this research, 4 inch (100mm) diameter specimens were loaded in compression at 1, 3, and 28 days after casting at a compressive stress of $0.3 f'_{ci}$. The specific creep of the specimens loaded after one

day saw a much greater asymptotic creep coefficient at 100 days ($\approx 1.59 \times 10^{-7}/\text{psi}$) than specimens loaded at 3 days ($\approx 1.21 \times 10^{-7}/\text{psi}$). The specimens loaded at 28 days ($\approx 1.01 \times 10^{-7}/\text{psi}$) had not yet appeared to reach an asymptotic value at 100 days (Burkart and Müller 2009).

Varying specimen sizes were also tested for specific creep; all specimens tested for size variance underwent the identical curing regimes and were loaded in compressive creep at 3 days after casting. Burkart and Müller concluded that the creep capabilities between the 4.0-in (100mm) and 6.0-in (150mm) diameter specimens showed no significant difference, however the 3.0-in diameter specimens seemed to have a higher asymptotic value for specific creep at $2.41 \times 10^{-6}/\text{psi}$. The average asymptotic specific creep value for the 4.0-in (100mm) and 6.0-in (150mm) diameter specimens were $1.45 \times 10^{-7}/\text{psi}$ and $1.24 \times 10^{-7}/\text{psi}$, respectively (Burkart and Müller 2008). These results allowed Burkart and Müller to conclude that the current DIN 1045 standard underestimates early-age creep response in UHPC.

In 2006 the Federal Highway Association (FHWA) published a report considering the early-age and long term unrestrained shrinkage and compressive creep characteristics of UHPC under varying curing regimes (Graybeal 2006). The four curing regimes administered to the UHPC included an ambient air cure, standard steam cure for UHPC, delayed steam cure, and a tempered steam cure (Graybeal 2006). The ambient cure consisted of curing the specimens in a climate controlled environment until time of testing; the standard steam cure employed a thermal treatment (194°F at 95% RH for 48 hours) 4 hours after specimens have been demolded, then the specimens were stored in a climate controlled room until the time of testing; the delayed steam cure

employed a thermal treatment 15 days after the initial casting date, after the thermal treatment specimens were stored in a climate controlled room until time of testing; the tempered steam cure was identical to the standard steam cure, however the temper steam treatment applied to the specimens 4 hours after demolding was only 140°F (60°C). Each of the four curing regimes was administered to the UHPC prior to any compressive load application.

Graybeal's long-term shrinkage testing of UHPC followed the ASTM 157 standard for length change in hardened NSC. Three specimen prisms with cross sections measuring 3 inches by 3 inches, and a length of 11 inches were cast with gage studs on the ends for each curing regime. After demolding, each specimen was subjected to an initial length reading prior to the application of the curing regime. Immediately following the curing regime a second measurement was recorded, in accordance with the ASTM 490 standard, and the specimens were stored in a temperature and humidity controlled room for the duration of measurements up to one year (Graybeal 2006). The delayed steam and standard steam cured specimens showed no shrinkage after the curing treatment, where the specimens subjected to the tempered steam and ambient cures showed continued shrinkage up to 4 months after the demolding (Graybeal 2006). The results of Graybeal's long-term shrinkage testing can be observed in Table 2.9 and Figure 2.1.

Graybeal's early-age shrinkage testing monitored the shrinkage strains in specimens over the first 17 days after casting. A vibrating wire strain gage was cast into the two prism specimens to monitor the resonate frequency of tensioned wired between embedded end blocks in the concrete. Gage measurements were manually taken in

Table 2.9
Long-term shrinkage (Graybeal 2006)

Curing Type	Premix Age at Casting (days)	Demolding Time (hours)	Ultimate Shrinkage (microstrain)
Steam	105	22.5	766
Untreated	55	22.0	555
Tempered Steam	50	22.0	620
Delayed Steam	47	23.0	657

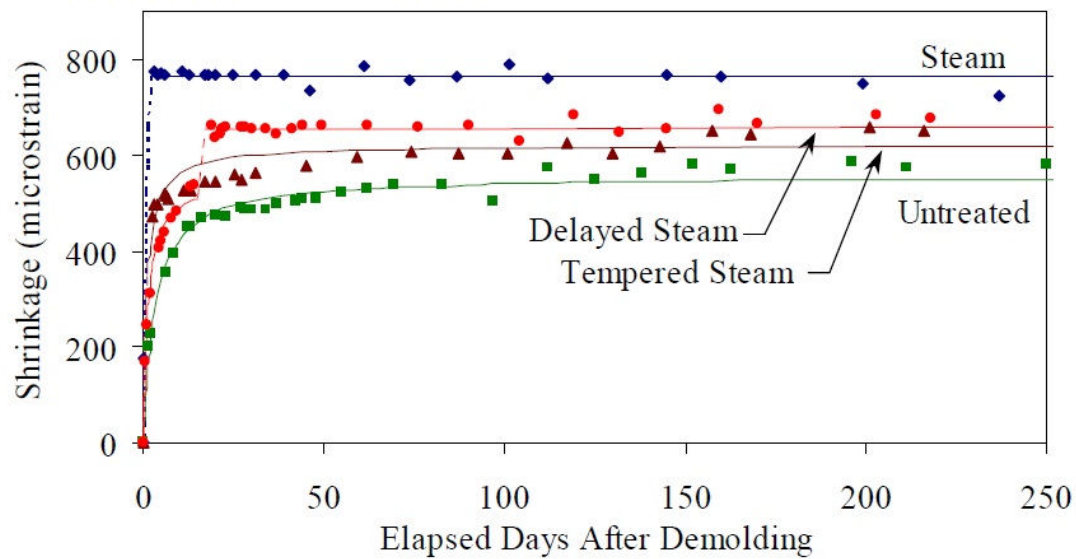


Figure 2.2 Long-term shrinkage results (Graybeal 2006)

accordance with ASTM 490 standard to verify the accuracy of the wire strain gage (Graybeal 2006). After demolding the prisms at 28 hours, one prism was subjected to the standard steam cure while the other prism was subjected to an ambient cure. Both specimens experienced rapid strain gain of 60 microstrain per hour immediately after the specimens were demolded. However, the prisms subjected to the steam cure experienced no additional shrinkage strains after the application of the standard

steam cure reaching an asymptotic value of 850 microstrain. The untreated specimen gradually reached 790 microstrain after 40 days of shrinkage monitoring. The results of the early-age shrinkage testing can be observed in Table 2.10 and Figure 2.3.

From the shrinkage monitoring Graybeal performed, it was confirmed that UHPC experiences most of the shrinkage strains immediately following demolding, as high as 60 microstrain per hour. It was also concluded that a tempered steam cure, standard thermal or delayed thermal cure, will accelerate the shrinkage of UHPC, and the UHPC will exhibit no post cure shrinkage strains. The untreated specimens will continue to gradually shrink but will eventually reach an asymptotic value slightly less than the specimens subjected to a steam cure (Graybeal 2006).

Table 2.10
Early-age shrinkage rates (Graybeal 2006)

Elapsed Time Since Casting (days)	Steam Treated shrinkage rate (microstrain per hour)	Untreated Shrinkage Rate (microstrain per hour)
0.0	0.0	0.0
0.8	0.0	0.0
1.0	20	20
1.1	36	36
1.2	64	64
1.3	—*	18
1.5	34*	3.5
1.7	11*	3.5
2.0	6.5	2.9
2.5	2.8	2.4
3.0	1.2	0.8
3.5	0.0	0.7
4.5	0.2	1.9
6.0	0.1	1.3
8.0	0.0	0.8
10.0	0.0	0.5

* Prisim was undergoing Steam treatment

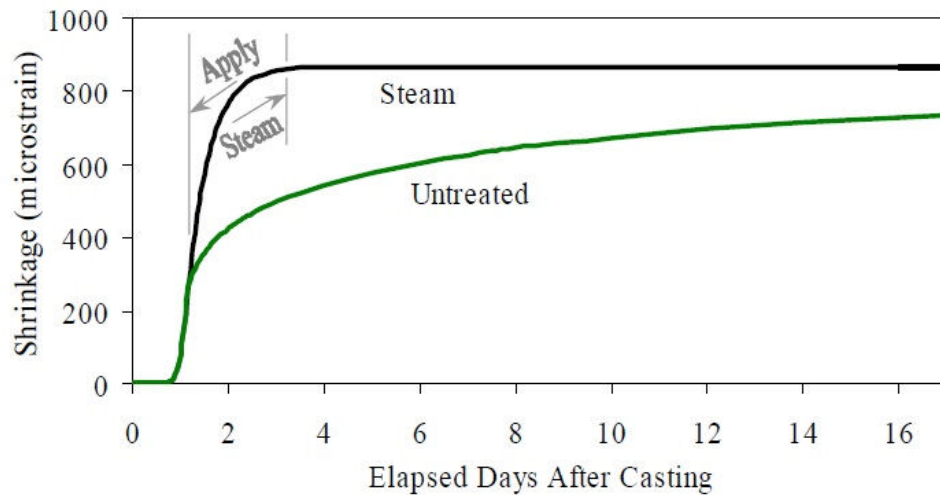


Figure 2.3 Early-age shrinkage (Graybeal 2006)

Graybeal conducted long-term compressive creep testing of UHPC in accordance to the ASTM C512 standard for compressive creep in NSC. Each curing regime would require four cylindrical specimens, measuring 4 inches in diameter and 8 inches in length with two 4 inch long cylinders to act a loading blocks. All of the cylinders were subjected to their specific curing regime, had their ends ground to within 0.5 degrees to meet plane and parallel requirements, and were instrumented with Whittemore points with a 6 inch nominal gage length before being stacked into a hydraulic actuated load frame (Graybeal 2006). The compressive creep load of 11.2 ksi was applied to cylinders, which approximately 40% of the 28 ksi anticipated compressive strength of the steam treated cylinders (Graybeal 2006). The standard steam and tempered steam cylinders were loaded at 4 days after casting, the delayed steam cured cylinders were loaded 21 days after casting, and the ambient cured cylinders were loaded 28 days after casting (Graybeal 2006). Once the load level was applied the specimens were placed in a temperature controlled environment for the duration of one year, in which Whittemore strain measurements could be recorded. Graybeal

noted that specimens subjected to a standard or delayed steam cure caused a more rapid self-desiccation of the UHPC resulting in less creep and thus a lower creep coefficient; while the specimens subjected to the tempered steam and ambient cures exhibit much higher creep coefficients (Graybeal 2006). Table 2.11 provides a summary of the average long term creep results for each of the curing regimes, and Figure 2.4 plots the average values of creep collected for each curing regime over the duration of one year.

Table 2.11
Long-term creep results (Graybeal 2006)

Curing Regime	Control Strength (ksi)	Stress/Strength	Initial Elastic Strain ($\mu\epsilon$)	Final Creep Strain ($\mu\epsilon$)	C_{cu}	δ_{cu} ($\mu\epsilon$ /ksi)
Steam	27.26	0.41	1500	440	0.29	39.3
Untreated	16.53	0.67	2057	1600	0.78	146
Tempered Steam	25.67	0.43	1670	1100	0.66	97.9
Delayed Steam	24.36	0.46	1580	485	0.31	44.1

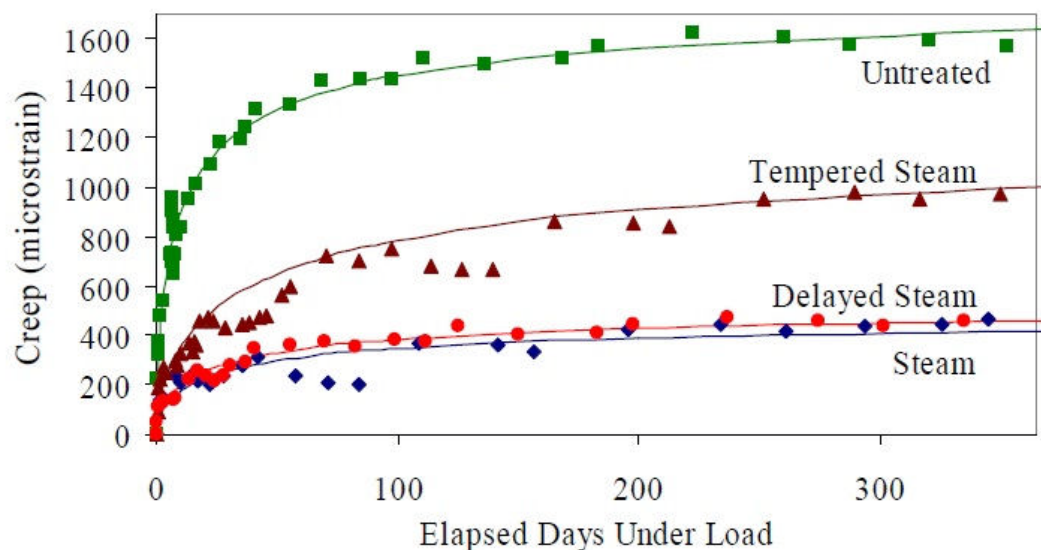


Figure 2.4 Long-term creep results (Graybeal 2006)

In addition to the long-term compressive creep testing performed by Graybeal, early-age compressive creep testing was also conducted to determine how much of the delay is necessary before stressing a prestressed UHPC girder. This testing set out to locate how much of the early-age UHPC strength can be utilized. One batch of UHPC cast 4 inch diameter specimens for early-age creep monitoring and 3 inch diameter specimens for compression testing. The 4 inch diameter cylinders were loaded at two load levels (8.5ksi and 12.5ksi), and monitored with three LVDT mounted on two parallel rings attached to the cylinders to measure axial deformations. The specimens were loaded at a rate of 150 psi per second until the desired load levels were reached (60% to 92% of the compressive strength), then held at that stress for 30 minutes before being unloaded at the same 150 psi per second rate (Graybeal 2006). Table 2.12 shows the early-age creep results and the following figures (Figure 2.5 and Figure 2.6) illustrate the creep behavior of the different load levels with respect to time in minutes for the lower load and higher load levels, respectively. The 30 minute creep coefficient C_{c-30} in Table 2.12 only represents the creep strain calculated over the 30 minute duration of the test. This 30 minute creep coefficient “equals the amount of additional creep strain that occurred during the 30 minutes divided by the initial elastic strain when the constant load level was reached” (Graybeal 2006). Therefore the C_{c-30} values calculated in Table 2.12 do not represent the standard creep coefficients and cannot be used to directly compare values of creep coefficients from long-term creep testing.

Table 2.12
Early-age creep results (Adapted from Graybeal 2006)

Cylinder Identifier	Compressive Strength (psi)	Applied Stress (psi)	Stress/Strength	C _{c-30}
7975 to 9425 psi Compressive Strength				
A1	9,425	5,655	0.6	0.42
A2	8,555	6,380	0.75	0.66
A3	9,280	7,830	0.84	0.79
A4	7,975	7,105	0.88	0.8
12,035 to 13,050 psi Compressive Strength				
B1	12,470	7,540	0.6	0.32
B2	12,180	8,845	0.73	0.39
B3	12,180	9,425	0.77	0.44
B4	12,180	10,150	0.83	0.52
B5	12,760	10,875	0.85	0.85
Failed Under Load				
A5	9,570	8,555	0.91	N.A.
B6	12,180	11,165	0.92	N.A.

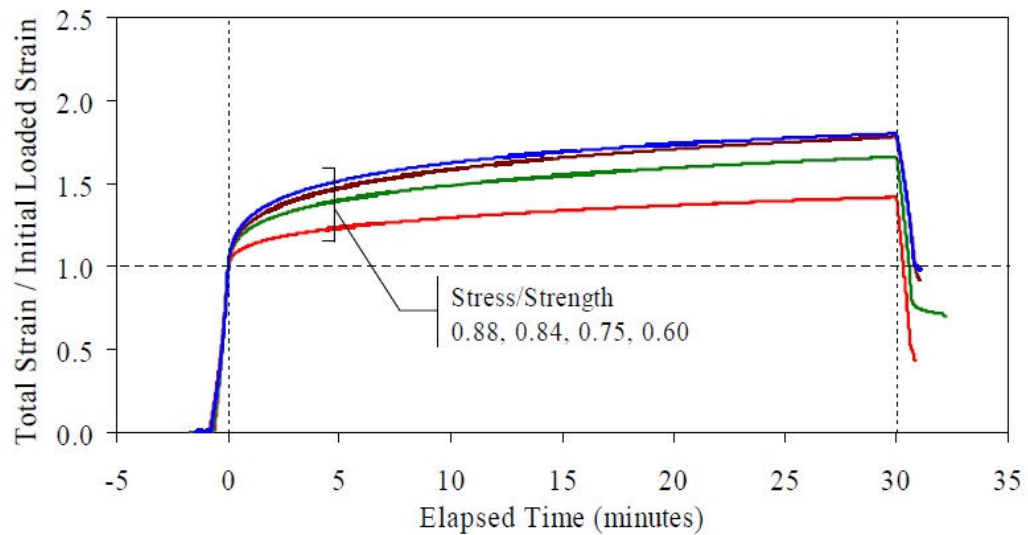


Figure 2.5 Early-age creep behavior 8.0 to 9.5 ksi (Graybeal 2006)

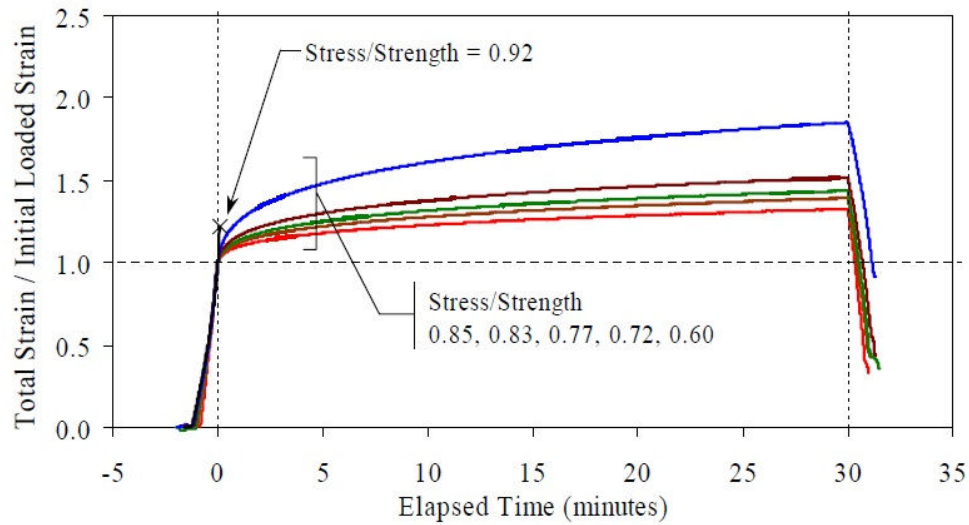


Figure 2.6 Early-age creep behavior of 12.5 ksi (Graybeal 2006)

It can be noted from Graybeal's tests that by applying a higher compressive stress to lower compressive strength specimens that higher creep values would result. This scenario would be expected of a prestressed UHPC beam with early release of prestress strands prior to the UHPC reaching the maximum compressive strength. The high creep results obtained in the early-age tests suggest that much higher creep levels would be predicted if the loading duration were equal to the long-term studies (Graybeal 2006).

2.3 Modulus of Elasticity

The modulus of elasticity is the measure for a specimen to deform (non-permanently) due to an applied axial force. This material property results in a mathematical relationship between stress and strain. The ASTM C469 standard "Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression" references a value for concrete on the elastic portion of the stress/strain curve up to 40 percent of the ultimate compressive strength ($0.4f'_c$). The linear slope of the elastic portion

of the stress/strain is the value for the modulus of elasticity. For concrete samples, testing for the modulus of elasticity can be difficult and time consuming; therefore several efforts have been made to develop a relation between compressive stress and the modulus of elasticity (Peuse 2008).

ACI Committee 318 has a relationship between compressive strength and modulus of elasticity E_c , for concrete with a 28 day compressive strength f'_c , and a unit weight w_c of 90 to 155 pcf. Equation 2.8 provides the ACI 318-08 equation in section 8.5.1.

2.8

$$E_c = w_c^{1.5} * 33\sqrt{f'_c} \text{ (psi)}$$

Because of high compressive strengths that UHPC is capable of reaching, the relationship in equation 2.8 is not accurate for UHPC. ACI Committee 363 produced a relationship between compressive strength and modulus of elasticity for HSC valid for concretes with compressive strengths ranging between 3,000 and 12,000 psi. Equation 2.9 provides the relationship model for HSC.

2.9

$$E_c = 40,000 * \sqrt{f'_c} + 1.0 * 10^6 \text{ (psi)}$$

The ACI committees provide relationships for the compressive stress and modulus of elasticity which do not satisfy the high strengths of thermally cured UHPC specimens. Additional code and recommendations, such as the Interim Recommendations for UHPC published by the Association Française de Génie Civil (AFGC) and by the Service d'études Techniques des Routes et Autoroutes (SETRA) also lacks a defined relationship between compressive strength and modulus of elasticity (AFGC/SETRA

2002). However, the document cites work performed at the Cattenom nuclear power plant on a relationship between compressive strength and modulus of elasticity and it is included in Equation 2.10 after converting to English units.

2.10

$$E_c = 262,000 * \sqrt[3]{f_{ATT}} \text{ (psi)}$$

Where:

$$f_{ATT} = \text{compressive strength of UHPC after a thermal cure (psi)}$$

A relationship developed in Japan with research focused on relating modulus on elasticity and compressive strength of high strength concretes was developed by Kakizaki et al. (1992). This relationship can be seen in equation 2.11.

2.11

$$E_c = 43,960 * \sqrt{f_c} \text{ (psi)}$$

Research within the U.S. has drawn conclusions on a relationship between the modulus of elasticity and compressive strength for UHPC at several universities. Research conducted at Iowa State University by Sritharan et al. (2003) on 3.0-in x 6.0-in. cylinders developed the relationship seen in equation 2.12.

2.12

$$E_c = 50,000 * \sqrt{f_{ATT}} \text{ (psi)}$$

In a dissertation at University of Maryland, Graybeal (2005) developed an additional equation that related compressive strength to the modulus of elasticity using ambient

air cured, thermally treated, and delayed thermally treated specimens. Graybeal's relationship can be seen in equation 2.13.

2.13

$$E_c = 46,200 * \sqrt{f'_c} \text{ (psi)}$$

As discussed in this literature review, creep and shrinkage data does exist for UHPC, however the studies performed to date are limited and not to the extent for complete understanding of these material properties for UHPC. Graybeal's work provided the most comprehensive study of creep and shrinkage on UHPC, most closely following U.S. based testing standards, employing curing regimes differing from the manufacturer's recommendation. However, Graybeal's work, as with all the research reviewed herein, only monitored creep and shrinkage after a thermal treatment had been administered to the specimens. Table 2.13 summarizes the curing regimes previously discussed before specimens were tested for creep and shrinkage strains. To-date, there is no published research studying a feasible scenario for the precast/prestress industry in the U.S. where UHPC specimens would be subjected to a compressive load before a thermal treatment. The compressive load would be applied prior to the completion of a thermal treatment, and continue through the duration of the thermal treatment and element life.

Table 2.13
Previous recommendations/literature curing regimes before compressive creep loading

	JSCE	SETRA	UNSW	Graybeal	Burkart and Müller
Early Age Ambient Cure				X	X
Full Strength Ambient Cure	X	X	X	X	X
Full Strength Thermally Treated	X	X	X	X	X
Tempered Steam Treatment				X	

3 Experimental Plan and Methodology

3.1 General Testing Information

The objectives of this chapter are to define the ASTM modifications for testing UHPC, cover the procedures and equipment used for mixing, casting and curing UHPC, and to introduce data acquisition used to collect the data. A total of seven batches of UHPC were tested in this research (two batches for strength gain studies, and five batches for creep and unrestrained shrinkage testing). The early-age strength gain studies were performed in early February, 2011 to locate the time, in hours, that the UHPC would reach the design recommended compressive strength of 14ksi for release of prestressing steel. Pre-steam cured and ambient air cured specimens were cast and tested using two separate UHPC batches. The five curing regimes tested for creep and unrestrained occurred over the 2011 summer months. Three creep frames recorded data on five curing regimes, requiring two of the creep frames to be unloaded and loaded with the second set of cylindrical UHPC cylinders.

3.2 Modification of ASTM Standards for UHPC

UHPC requires modifying the current ASTM standard test methods for NSC. Section 2.2.1 outlines the methods used for testing creep and unrestrained shrinkage in NSC specimens. Although some modifications were necessary, areas of the ASTM standard test methods that could remain unaltered were carried out in accordance with the specifications. The following sections describe the changes, and reasons why the changes were carried out in this research.

3.2.1 Stress Levels

A design recommendation for compressive strength of UHPC at the time of prestress release is at 14ksi. A goal of this research is to provide creep and unrestrained shrinkage results to the precast/prestress industry, the required release strength was the basis for determining the loading levels. Previous research has shown that compressive loading on UHPC has occurred at compressive strength levels other than the recommended minimum of 14 ksi, however, the research reported herein only focuses on the five distinct curing regimes as the testing variable at two allowable load levels.

The creep test procedure outlined in the ASTM C512 standard (ASTM 2010) was modified for this research. The ASTM standard specifies that a maximum compressive load be only 40% of the compressive strength at the time of loading for creep monitoring. For this research, two creep frames were positioned on a movable cart and monitored together. This allows for two stress level scenarios for the same curing regime. The higher of the two stress levels was the ACI 318-08 committee allowable compressive stress, per 18.4.1a, from the prestressing steel tendons, which is 60% of the compressive strength of the concrete at the time of loading, $0.6f'_{ci}$. This value is higher than the ASTM standard allows for the maximum stress level, resulting in a compressive stress of 8.4 ksi for a 3.0-in. diameter cylindrical specimen. The second stress level that was tested was much lower at $0.2f'_{ci}$, to investigate the reaction of UHPC to lower stress levels. This lower stress level, resulting in a compressive stress of 2.8 ksi, was applied to observe the reaction of UHPC under lower stress levels.

3.2.2 Horizontal Molds

All test specimens in this research were cylindrical specimens. The diameter of the specimens was consistent at three inches. Compressive test specimens had length of six inches, and creep and unrestrained shrinkage specimens had a length of 12 inches (Figure 3.1). These dimensions were modified from the ASTM C512 and the ASTM C157 standards for both the creep and unrestrained shrinkage tests (ASTM 2010). Due to the high compressive strength of UHPC, and the quick loading of the specimens at a specific time intervals, horizontal molds were used to ensure flat and perpendicular end requirements described in ASTM C617 (ASTM 2010) without manually saw-cutting, end grinding, or sulfur capping the specimens. Steel molds were fabricated for both specimen sizes with a 1 inch slot cut along the length of the molds for filling with UHPC. The 3.0-in. diameter specimens allowed for the ability to cast all the required test specimens from a single 18 liter batch of UHPC for each curing regime. The unrestrained shrinkage specimens used in this research were cast identical to the creep specimens, which allowed for consistent measurements between the creep and

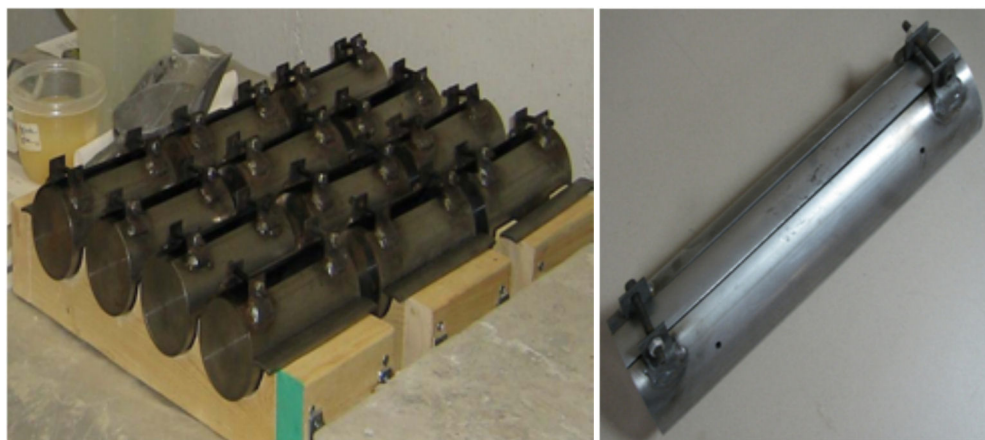


Figure 3.1 6.0-in. horizontal steel molds on wood racks, and 12.0-in. creep and shrinkage mold

shrinkage specimens. Similar techniques for measuring specimen dimensions and gage lengths remained consistent throughout this research.

3.2.3 Instrumentation

The ASTM C512 standard specifies that horizontally cast specimens shall not be used for external strain measurements. However, the molds used in this research and previous research has suggested that a consistent cross section can be maintained, which will provide accurate external strain measurements (Burkart and Müller 2008). Monitoring external strain in these samples was possible through two sets of three brass inserts that were embedded in the UHPC specimen at 120° intervals around the specimen. The two sets of brass inserts were positioned eight inches apart (gage length of 8.0-in), and dimensional changes were based in the position change of these brass insert pairs. Gage studs were used to both, hold the brass inserts in place during casting and curing, as well as provide a single point for the external strain measurements to be taken. Figure 3.2 shows a brass insert and gage stud used in this research. External measurements were monitored by a Whittemore strain gage (Figure 3.3), which measures length change over time. Internal strain gages embedded in the specimens

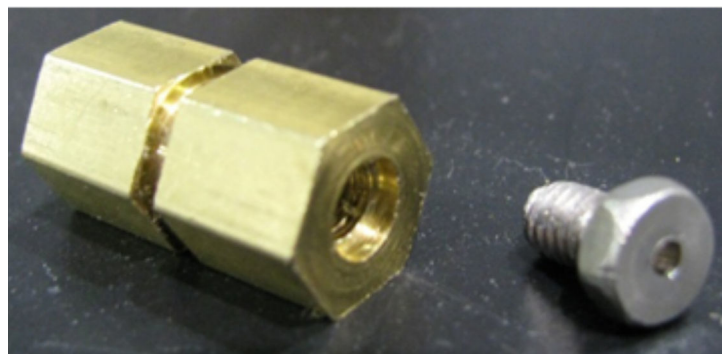


Figure 3.2 Brass insert and gage stud



Figure 3.3 Whittemore strain gage

may malfunction during the curing processes due to the high heat and relative humidity in the curing chambers and thus, were not included in this research.

Before loading the specimens into the creep frames, the dimensions were measured. A total of three diameter measurements and three lengths were taken to determine the average diameter and length of each specimen. Compressive testing on additional compressive cylinders (3-in x 6-in) was performed prior to the compressive creep loading.

Each specimen was labeled according to the curing regime, load level applied, and specimen number under the high or low level load. In addition to the specimen identification written on the cylinder, each gage length was numbered “G₁, G₂, or G₃” and an initial reading was recorded on both the creep and shrinkage specimens prior to the application of compressive creep loading. Once the specimens were under the creep load, each gage length was measured again to determine the average initial elastic strain, $\epsilon_{initial}$. Unique gage identification on each cylinder allowed for dimensional changes of each gage length to be monitored individually. Gage length measurements of both the creep and shrinkage specimens were monitored four hours

after the initial loading time, then daily until the time of one week had passed, and then weekly for one month.

3.2.4 Creep Frames

The design of the creep frames used in this research was based on the recommendations outlined in the ASTM C512 standard. The goal was to design a frame that would meet all the requirements of this research, and also be useful in future research. Loading scenarios involving of both UHPC and NSC were considered using a range of diameter sizes from 3.0-in. to 6.0-in, and compressive loads of $0.2f'_{ci}$ to $0.6f'_{ci}$ and $0.4f'_c$. Loads were modified from the ASTM C512 standard for maximum compressive stress and the to the ACI 318-08 committee maximum stress level due to prestress transfer. Nyland (2009) found that the maximum compressive stress that the creep frames must maintain was the $0.4f'_c$ compressive stress of 151 kips for a 4-in. diameter UHPC cylinder. It was also determined that the loads of interest for that research would be 20 kips for the $0.2f'_{ci}$ stress level, and 59 kips for the $0.6f'_{ci}$ stress level (Nyland, 2009). Table 3.1 summarizes all of the loading scenarios considered for the use of the creep frames.

Table 3.1
Creep frame stress level investigation (Nyland, 2009)

Concrete Type	Section Diameter (in)	X-sect. Area (in ²)	Stress/Load Level							
			$0.2f'_{ci}$		$0.4f'_{ci}$		$0.6f'_{ci}$		$0.4f'_c$	
			ksi	kip	ksi	kip	ksi	kip	ksi	kip
UHPC*	3	7.07	2.8	20	5.6	40	8.4	59	12	85
	4	12.57	2.8	35	5.6	70	8.4	106	12	151
NSC**	4	12.57	1.6	20	3.2	40	4.8	60	4	50
	6	28.17	1.6	45	3.2	90	4.8	136	4	113

*Assuming $f'_c=30$ ksi, and $f'_{ci}=14$ ksi for UHPC

**Assuming $f'_c=10$ ksi, and $f'_{ci}=0.8$ ksi for NSC

Maximum load of interest
Load of interest

Construction of the creep frames consisted of (4) steel square distribution plates, measuring 12.0-in. in width and 3.0-in. in height. The specimens were loaded against a spherical bearing assembly installed with guide pins to align and alleviate the possibility of eccentric loading. The creep frame was held together by (4) 1.5-in diameter steel threaded rods to take the reaction from the applied loads (Nyland 2009). The load was applied using a 200 kip capacity Enerpac® CLP-1002 hydraulic cylinder, and a 76.5 kip capacity Schnorr® standard disc spring (Figure 3.4). The applied loads were monitored by a Transducer Techniques® model CLC-200K (200 kip capacity) load cell, which output the load reading on a Transducer Techniques® DPM-3 data acquisition system (Figure 3.5) (Nyland 2009). Creep frames were installed in pairs on movable carts for ease in applying the thermal cures at varying times.

The mechanical system responsible for maintaining constant hydraulic pressure on the hydraulic jack utilized the internal compressed air system in the lab facilities (100psi). A pneumatic/hydraulic pump was installed on a cart separate from the creep frames; which allowed the pump to be outside of the curing chamber while only the specimens were subjected to the thermal cure. The pneumatic/hydraulic pump utilized for the loads of interest on the creep frames were a SC Hydraulic Engineering Corp® D5 series model 85, which was capable of supplying 8,600 psi of hydraulic fluid at 100 psi of air pressure. The high efficiency ratio 86:1 of the D5-85 pump allows for all the compressive stress loads to be applied (per the stress level investigation), and will not exceed the maximum capacity of the 200 kip capacity Enerpac® CLP-1002 hydraulic cylinder. Air pressure coming into the system was monitored by an air pressure regulator. This supplied constant air pressure on the pneumatic/hydraulic pump, continuously allowing the pump diaphragm to pump hydraulic fluid to the 200 kip



Figure 3.4 76.5 kip capacity Schnorr® standard disc and 200 kip capacity Enerpac® CLP-1002 hydraulic cylinder



Figure 3.5 Transducer Techniques® model CLC-200K load cell and DPM-3 data acquisition system

capacity Enerpac® CLP-1002 hydraulic cylinder. However, through trial runs with the creep frame system, it was observed that a pressure spike was induced from the pneumatic/hydraulic pump to the load cell every time the diaphragm in the pump released. The pressure spike was unpredictable in both pressure applied to the system and amount of pressure drop needed from the system. A manual BVA® model CVR3 pressure control/relief valve was installed on the hydraulic line which would limit the amount of hydraulic pressure applied to the 200 kip capacity Enerpac® CLP-1002 hydraulic cylinder, and recycle the excess hydraulic fluid to a VESCOR® vertical

hydraulic reservoir. After installation and setting of the pressure control/relief valve to adequate parameters, the hydraulic pressure supplied to the 200 kip capacity Enerpac® CLP-1002 hydraulic cylinder leveled out and constant load readings were observed by the CLC-200K (200 kip capacity) load cell and read on the DPM-3 data acquisition system. A hydraulic cut-off valve was installed on the hydraulic line directly connected to the 200 kip capacity Enerpac® CLP-1002 hydraulic cylinder. The cut-off valve stopped the flow of hydraulic fluid providing a constant hydraulic pressure while the creep frames were moved in and out of the curing chamber. Three eights inch hydraulic hose lines capable of 4800 psi were used throughout the system. Figure 3.6 shows the complete creep frame system in operation, and process flow diagram of the mechanical operation is included in Appendix A.

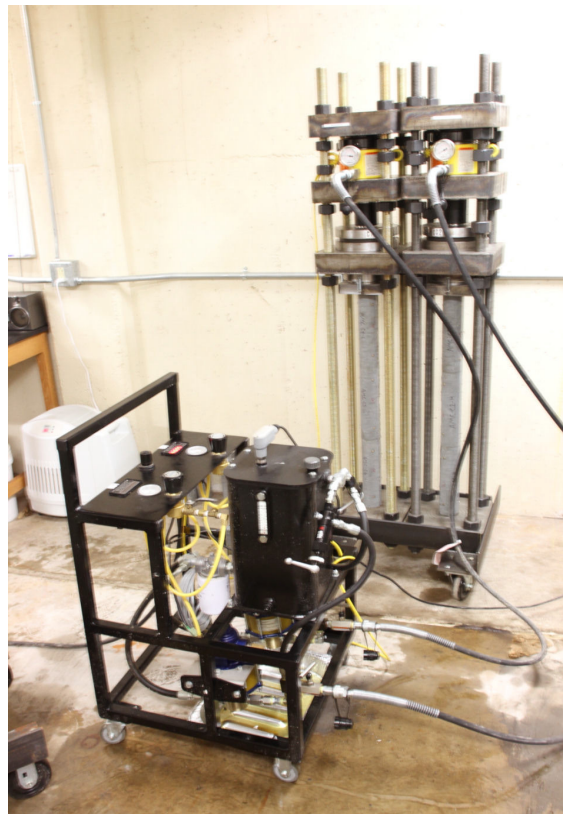


Figure 3.6 Creep frame pair with separate pneumatic/hydraulic pump cart

3.3 Preparation Methods

The UHPC batches mixed and cast in this research all used the same mix proportions and procedures, equipment, molds, and were tested using consistently identical methods. All of the Ductal® premix and superplasticizer was from the same shipping order.

3.3.1 Batching Procedure

Each batch of UHPC used in this research had identical proportions of the constituents. The premix, consisting of the majority of the batch was measured using a 300 lb scale with a precision of 0.05 lbs. All other constituents were measured on a 33 lb scale with a precision of 0.01 lbs. The 18 liter batch total weight is 101.9 lbs. Table 3.2 lists the weight (lbs) of an 18 liter (0.63ft³) batch of UHPC mixed at Michigan Tech.

3.3.2 Mixing Procedure

All batch mixing times and conditions can be observed in Appendix B. This research used consistent mixing procedures using a 2.0ft³ Doyon planetary mixer (Figure 3.7)

Table 3.2
Batch composition at Michigan Tech

Constitute	Proportion (weight lbs)
Ductal BS1000 Premix	87.05
Steel Fibers (8x10-3-in. dia. by 0.5-in. long)	6.19
Water	5.11
Superplasticizer (Chryso Premia 150)	1.19



Figure 3.7 Doyon planetary mixer

developed by Kollmorgen (2004). Mix times varied slightly due to UHPC break times and batch sizes, but remained consistent with UHPC mixes carried out at Michigan Tech as seen in Kollmorgen (2004), Misson (2008), Peuse (2008), and Nyland (2009).

3.3.3 Testing Consistency

Prior to casting any UHPC specimens, a flow test outlined by the ASTM C1437 standard (ASTM 2010) for the flow of hydraulic cement was performed as recommended by the Ductal® reference T 006 (Larfarge NA 2003). Figure 3.8 shows the brass cone mold and flow table used during this test. Immediately after the UHPC mix was complete this flow test would take place to determine workability and pot life of the UHPC batch. The brass cone mold and flow table would be dampened just prior to the test. The brass cone mold would be centered on the flow table and then filled with UHPC. Any excess UHPC would then be stricken off and the brass cone mold would be lifted straight up over a period of 4-5 seconds. Any UHPC left in the brass cone would be



Figure 3.8 Brass cone mold and flow table

removed and placed in the center of the UHPC on the flow table. After a period of 60 seconds passed, 4 diameter reading of the UHPC spread would be measured. After the fourth recording the table would be mechanically dropped a distance of 0.5 inches twenty times and the spread of UHPC would be measured again. The domain of the mix could be determined by the average diameter of the UHPC spread; less than 200 mm would be a stiff mix, between 200 mm and 250 mm would be classified as a fluid mix, and over 250 mm would result in a highly fluid mix. All of the batches mixed in this research fell into the fluid mix domain.

3.3.4 Casting of Specimens

Before casting of the horizontal molds could take place, a thin layer of mineral oil was applied to the inside of the molds to allow for easy removal of the UHPC. In addition

to the mineral oil, the horizontal steel molds (Figure 3.1) required additional preparation; the ends of the molds were held against a flat surface as the mold was tightened to provide plane and parallel ends when cast.

All horizontal molds were cast in a similar manner. The molds were placed on wood racks (4 specimens per wood rack) and filled at one end of the mold allowing the UHPC to flow down the length of the mold. Only one lift was used in accordance with the ASTM C192 standard for horizontal molds used for making prisms. After the UHPC had time to flow and fill the entire mold, the specimens were placed on a vibrating table to consolidate the UHPC releasing all of the air bubbles in the mold (8-10 seconds). The vibrating table maintained a 0.02-in. amplitude as recommended by the Ductal® reference T 002 (Larfarge NA 2003). Any overflow of UHPC on the molds was struck off and the top of the molds were fitted on and secured with duct tape. The specimens were then placed in an ambient cure room until all of the specimens were cast. Once the entire batch was cast the appropriate curing regime was administered; “end of casting” would be used as the “zero” starting point for the various tests.

3.4 Curing Regimes Defined

The goal of this research is to mimic conditions selective to UHPC creep and shrinkage procedures of current precast/prestressed plants in the U.S. to allow for a clear understanding of these conditions and procedures on future design codes. The use of a steam cure immediately after concrete is placed in the prestressing beds is commonly used in precast/prestressed plants around the U.S. The steam cure will accelerate the concrete compressive strength gain and therefore allow the release of the prestressing strands earlier, which reduces cycle time of the prestressing beds.

From previous interviews with precast/prestress facilities using NSC and HSC “it was determined that (regardless of climate) cure temperatures prior to prestress release are maintained between 75-95°F for approximately 3 hours immediately following casting; the cure temperature is then slowly raised, over a period of 2-3 hours, to a maximum temperature between 120-150°F, where it is maintained until the forms are stripped and the prestress is released (at ≈12-15 hours from casting)” (Nyland 2009).

The five curing regimes chosen for this research aimed to mimic several scenarios expected at precast/prestressed plants. Recall from Table 1.2, four curing scenarios involved the use of a thermal cure (194°F (90°C) at 95% RH for 48 hours) while under a compressive load. In addition, an ambient curing regime will be used as a baseline for comparison. A pre-steam cure (140°F (60°C) at 95% RH) was also administered to accelerate the compressive strength of the specimens.

The pre-steam cure was implemented on three curing regimes, while the remaining curing regimes were ambient cured. As previously stated, the time in which all the specimens of a single batch were placed into the curing chamber for the pre-steam treatment or placed in the ambient conditions, was the reference “zero” starting point for the tests. This pre-steam treatment consisted of raising the chamber temperature to 140°F (60°C) over a 3 hour period and then holding at 140°F for the next 14 hours. In order for UHPC to “lock in” its high compressive strength and durability characteristics, a thermal cure is required. In all cases the thermal cure occurred after the creep loading was applied to the specimens. The thermal treatment required moving the creep frames into a custom built curing chamber, as seen in Figure 3.9 where the temperature will gradually increase to 194°F (90°C) over



Figure 3.9 Michigan Tech's custom creep frame curing chamber

a 6 hour period, holding at 194°F (90°C) for 48 hours before the specimen are cooled down by ambient air. An image of the compressive specimens undergoing the thermal cure can be seen in Appendix F.

Nomenclature for the specimens tested included the abbreviated curing regime (as outlined in following sections), specific test being performed on the specimen, stress level applied to the specimen, and individual number system. The amount of data recorded on each individual specimen required a unique specimen name. For all specimens, the three letter abbreviation for each curing regime was recorded; AMC, SST, PST, PDT, and PDD. Depending on the test (creep, shrinkage, and compression) an identifier was given, with a cylinder number. For creep testing, cylinders were identified as C1 through C6; shrinkage specimens were identified by S1 through S3 and compression specimens were identified as COMP-1 through COMP-3. In addition for the creep specimens, a high or low indicator represented which load level was applied to that specific specimen. The final indicator that will be recorded on the creep

specimens was “H” for the high load stress of $0.6f'_{ci}$ (8.4ksi) and “L” for the low load of $0.2f'_{ci}$ (2.8ksi). A specimen sample with the identification of “PST-C4-L” which would be identified as a specimen subjected to the pre-steam/thermal curing regime; the specimen was 4th cylinder in the batch, and subjected to the low creep stress level load. The specimen identified as “AMC-S2” was subjected to the ambient air cure regime, and was the second cylinder in the shrinkage test. A specimen labeled as “PDD-COMP-1” would have been subjected to the pre-steam/double delayed curing regime; and was the 1st compressive sample to be tested.

Ambient air cured specimens, and when the remaining specimens were not undergoing a pre-steam or thermal treatment, were stored in a temperature and humidity controlled room. The ASTM C157 standard conditions required the room to be maintained at a temperature range of $73.5^{\circ}\text{F} \pm 3.5^{\circ}\text{F}$ and relative humidity range of $50\% \pm 4\%$. The room was equipped with an air-conditioner to control the temperature and a humidifier/dehumidifier system to balance the relative humidity of the room. The temperature and relative humidity was monitored by an Extech[®] RHT20 humidity and temperature data logger which recorded values at ten minute intervals through the duration of the experiments. The ambient controlled room was sealed off from the remainder of the lab; the doors were only quickly opened for days that required strain readings and moving the creep frames to and from the thermal curing chamber.

3.4.1 Ambient Air Cure (AMC)

Implementing the ambient air cure involved batching and casting the UHPC as previously described and allowing the UHPC to cure in an ambient air environment at 73°F (23°C) and 50% relative humidity. The specimens cured until the target

compressive strength of 14 ksi was reached at approximately 70 hours. At that time the creep specimens were loaded into the creep frame where they continued to cure in ambient conditions. The AMC was the only curing regime not to incorporate a thermal cure. The graph in Figure 3.10 shows the cure temperature (°F) and the applied stress level with respect to elapsed time from the “zero” starting point, relative to the end of casting in hours.

3.4.2 Standard Thermal Cure (SST)

Before applying the creep load to the standard thermal cure specimens, the UHPC specimens were placed in an ambient cure room until the target compressive strength of 14 ksi was reached at 70 hours. Once the creep specimens were loaded in the creep frames, the standard thermal cure was applied for the next 48 hours. The SST will mimic what would be expected for a precast/prestress plant to release the prestressing tendons and immediately administer the thermal cure; an upper bound for a precast plant wanting to treat immediately following removal of the UHPC beams from the precast beds. The graph in Figure 3.11 shows the cure temperature (°F) and the applied stress level with respect to elapsed time from end of casting in hours.

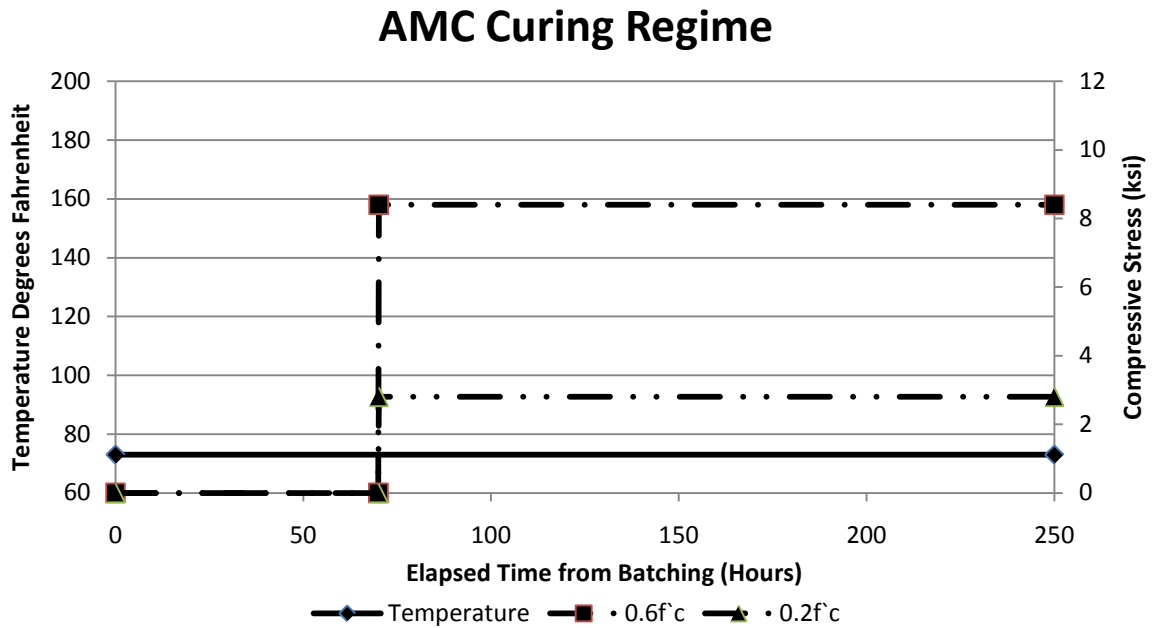


Figure 3.10 AMC applied creep stress level and cure temperature variation with respect to specimen age

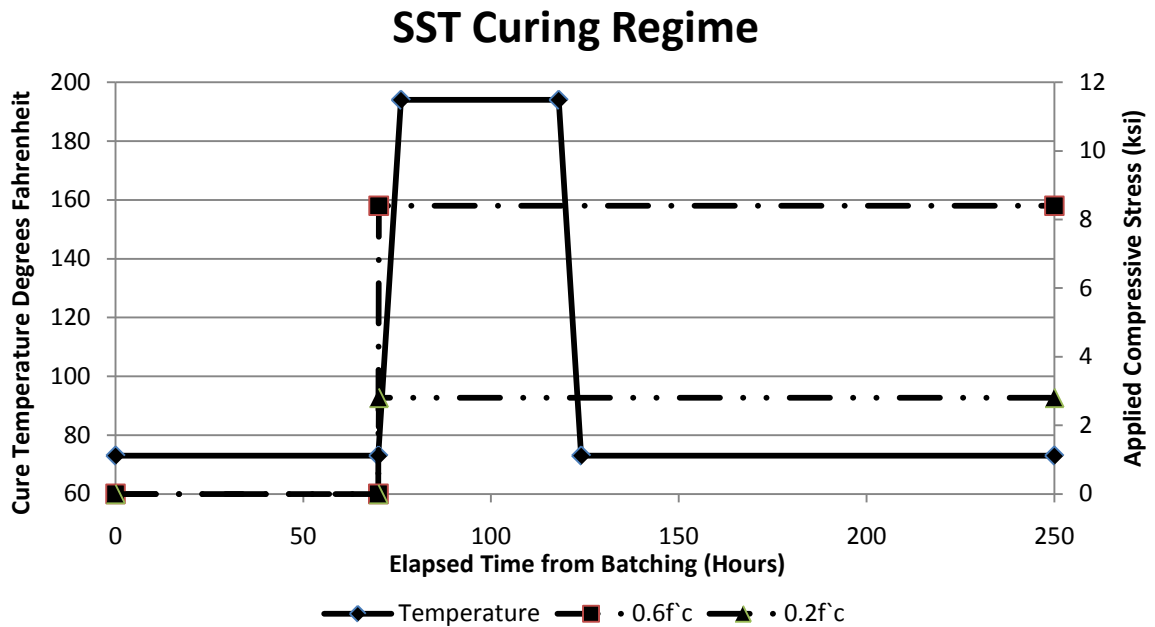


Figure 3.11 SST applied creep stress level and cure temperature variation with respect to specimen age

3.4.3 Pre-steam/Thermal Cure (PST)

The pre-steam/thermal cure is similar to the SST, but accelerates the time to the target compressive strength of 14 ksi, down from 70 to 14 hours due to the use of a pre-steam cure. After all of the specimens were cast, they were placed into the curing chamber for the pre-steam treatment. When the target compressive strength was reached the specimens were placed under the creep loading and immediately placed into the thermal curing chamber for a period of 48 hours. After the specimens were removed from the curing chamber they were stored in an ambient controlled room ($73.5^{\circ}\text{F} \pm 3.5^{\circ}\text{F}$ at $50\% \pm 4\%$ RH) with external strain measurement recorded at the predetermined time intervals (per ASTM C512). The PST regime mimicked what would be expected for a precast/prestressed plant steam curing the specimens to accelerate the target compressive strength, then release the prestressing tendons and immediately administer the thermal cure, perhaps reclaiming some energy/steam from the pre-steam cure. The graph in Figure 3.12 shows the cure temperature ($^{\circ}\text{F}$) and the applied stress level with respect to elapsed time from end of casting in hours.

3.4.4 Pre-steam/Delayed Thermal Cure (PSD)

The graph in Figure 3.13 shows the PSD curing regime, plotting the cure temperature ($^{\circ}\text{F}$) and the applied stress level with respect to elapsed time from end of casting in hours. The pre-steam/delayed thermal cure is similar to the PST, the difference coming in the lag time between the applied creep loading and the thermal cure application. Once the target compressive strength of 14 ksi was reached and the creep loads were applied, a delay of 72 hours occurred before the thermal cure was

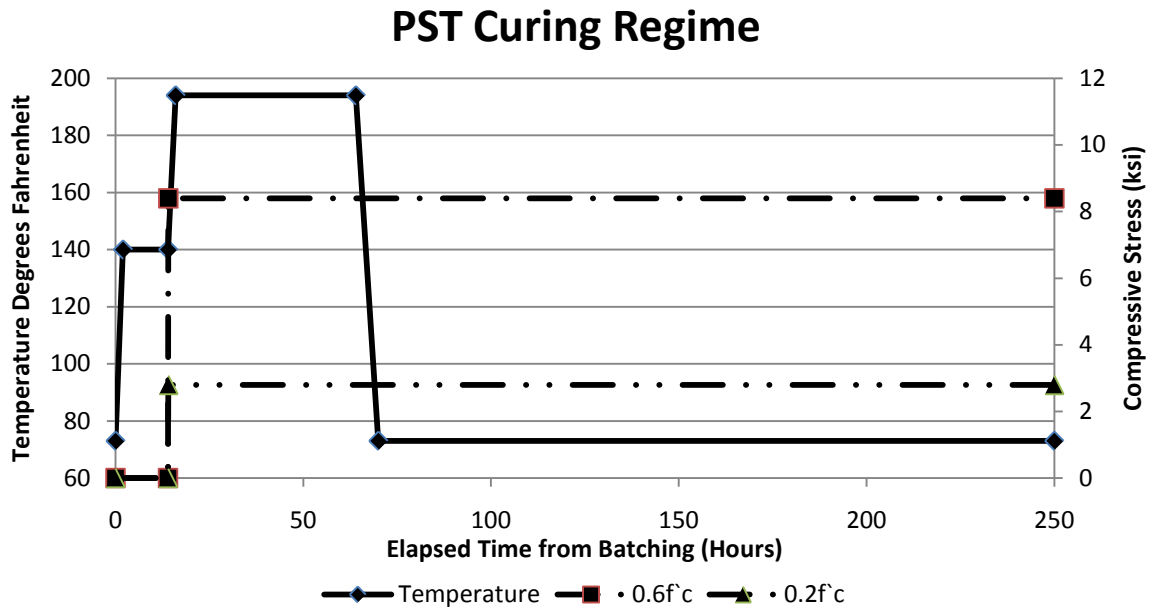


Figure 3.12 PST applied creep stress level and cure temperature variation with respect to specimen age

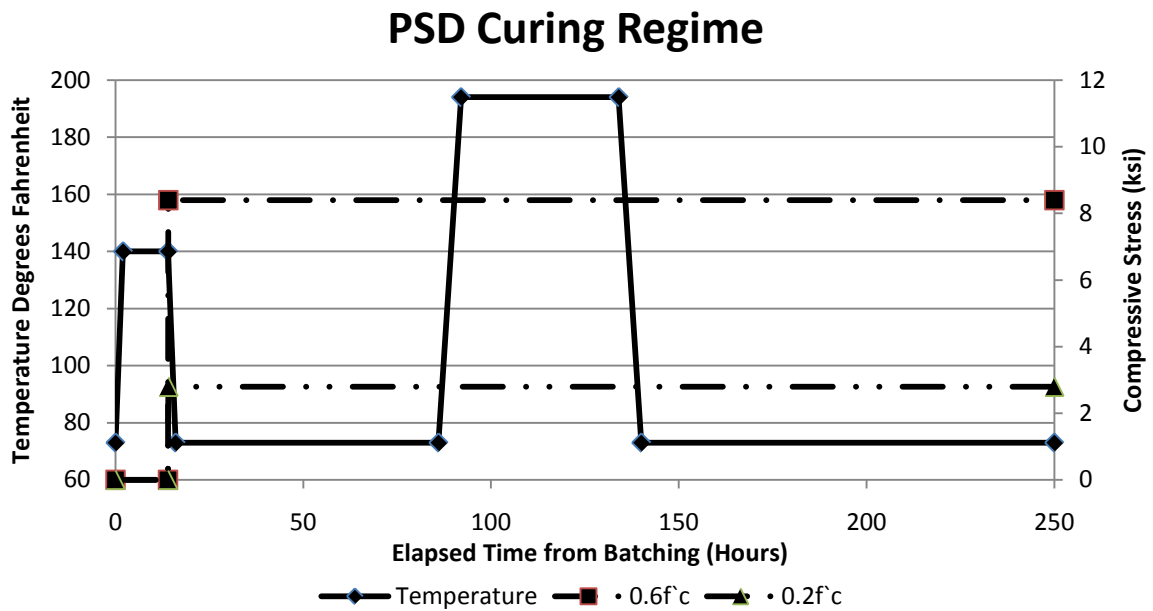


Figure 3.13 PSD applied creep stress level and cure temperature variation with respect to specimen age

administered to the specimens. After the specimens were removed from the curing chamber they were stored in an ambient controlled room for the duration of the

study. The PSD regime will mimic what would be expected of a precast/prestressed using a pre-steam treatment to accelerate the target compressive strength, and then release of the prestressing tendons. A lag time of 72 hours could occur before the thermal treatment would be applied, which could be due to storing the specimens until more UHPC products are produced. Then thermal curing all of the products would occur simultaneously, conserving energy costs of the thermal cure. The external strain measurements recorded on these specimens will determine if lag time will have any effect of the creep and shrinkage strains after a thermal treatment is administered.

3.4.5 Pre-steam/Double Delayed Thermal Cure (PDD)

The final curing regime tested in this research was a pre-steam/double delayed thermal cure. The PDD is almost identical to the PSD regime, with the only change being a longer lag time between applied creep loading and application of the thermal treatment. Once the target compressive strength of 14 ksi was reached and the creep loads are applied, a delay of 11 days occurred before the thermal cure was applied to the specimens. This longer delay was implemented to identify any significant affects on the creep characteristics undergoing a compressive load before the application of a thermal treatment. Prior to, and after the specimens were in the curing chamber they were stored in an ambient controlled room. The longer lag time will allow for delay in applying a thermal cure due to precast/prestress plant procedures, and aid in determining if a lag time has any affect on UHPC after a thermal cure is applied. Figure 3.14 shows the timeline for the PDD curing regime.

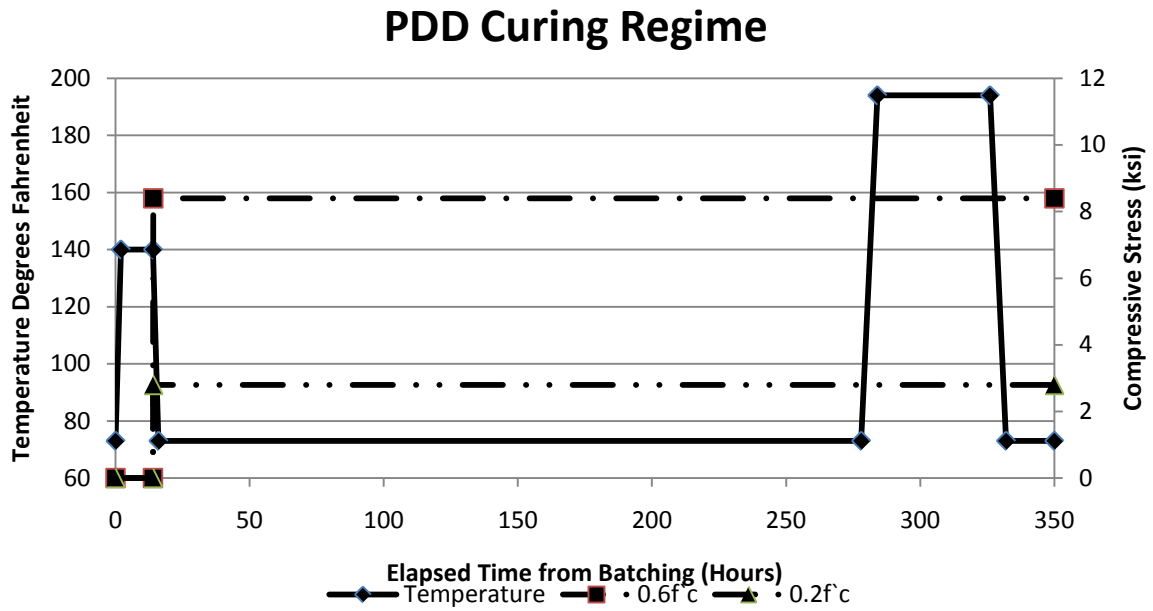


Figure 3.14 PDD applied creep stress level and cure temperature variation with respect to specimen age

3.5 Testing

3.5.1 Compression Testing

Testing to failure of UHPC in this research was done in compression with the Baldwin CT 300 hydraulic load frame compression testing machine with an adjusted loading rate of 150 psi/s as recommended by the Ductal® reference T001. The increased load rate is altered from the ASTM C39 standard of 35 psi/s \pm 7psi/s (ASTM 2010) in order to reduce the length of the test staying in accordance with the ASTM C39 time frame of three minutes (Peuse 2008). The specimens are positioned between two steel bearing plates and loaded to failure where the maximum compressive load value is recorded.

3.5.2 Reproduction of Strength Gain Studies

To locate the target compressive strength of 14 ksi to apply the creep loading on the specimens, compressive strength gain studies had to be performed on the ambient and

pre-steam cured specimens. Previous research at Michigan Tech located the compressive strength of 14 ksi at 86 hours and 18.5 hours for the ambient cured and pre-steam cured specimens, respectively (Nyland 2009). However, reproduction of these studies was performed due to minor changes in the Ductal premix (due to changes in filler material). By testing for the gain in compressive strength, accurate prediction of the compressive strength can be determined by the specimen age.

3.5.2.1 Ambient Cure Compressive Strength Gain Study

The early-age ambient compressive strength was needed for two curing regimes in this research (AMC and SST). Specimens were cast in 3.0-in. diameter by 6.0-in. horizontal steel molds for compression testing. The horizontal molds provided the plane and parallel end requirements per the ASTM C617 standard, without the need for sulfur capping. Prior to testing the UHPC specimens, diameter readings, length readings, and weights were recorded to calculate averages for the specimens. Once all the specimens were cast, the curing time began referencing the *batch life* at t_0 . This time marked the beginning of the curing regimes and is significant in the timeline for compressive loading of the specimens. A specimen was randomly selected from the batch of specimens for compressive loading beginning at 50 hours (t_{50}) from the initial batch life. Specimens were tested in pairs for an average compressive strength recording. Depending on the average compressive strength at 50 hours, consistent interval testing, occurring at half hour increments was administered to locate the target compressive strength. Specimen nomenclature was identified as AMC-1C-##, where the following number signs indicated the age, in hours, from initial batch life; for example AMC-1C-60 is a specimen test that was subjected to an ambient air cure and tested 60 hours after the initial batch life.

3.5.2.2 Pre-steam Cure Compressive Strength Gain Study

The early-age pre-steam compressive strength investigation was implemented on three curing regimes in this research (PST, PSD, and PDD). Specimens were cast and measurements were recorded as described on the ambient cured specimens in section 3.5.2.2. Immediately following the completion of the casting, the specimens were placed in a steam fed chamber which involved a 2 hour ramp up cycle from ambient air temperature (72 °F) to 140°F with a relative humidity of 95%. Once all the specimens were cast and placed in the curing chamber, the curing time referenced for the *batch life* at t_0 . A specimen was randomly selected from the batch of specimens for compressive loading beginning at 14 hours (t_{14}) from the initial batch life. Specimens were tested in pairs for an average compressive strength recording. Consistent interval testing was administered at one hour intervals to locate the target compressive strength. Specimen nomenclature was identified as PSC-1C-##, where the following number signs indicated time from initial batch life; for example PSC-1C-20 was subjected to the pre-steam cure and tested 20 hours after the initial batch life.

3.5.3 Varying Curing Regimes Compressive Creep and Companion Shrinkage Monitoring

The load maintained on the specimens and the room temperature and humidity conditions were monitored constantly to verify that the tests were in accordance with the ASTM C512 standard and the ASTM 157 standard. Manual gage measurements were performed as outlined in the ASTM C512 standard with a Whittemore strain gage. Timing was crucial in mimicking standard U.S. precast/pre-steam plant procedures, and timeline documentation was recorded throughout the curing regime tests. The beginning of each test started at time zero, t_0 , which was the time the UHPC batch

had been cast into the horizontal steel molds and either the pre-steam or ambient curing regime has begun. When the UHPC reached a compressive strength of 14 ksi (t_{14hrs} and t_{70hrs} for pre-steam and ambient specimens respectively) the specimens were demolded and loaded in the creep frame. After initial gage measurements were taken, the ASTM C-512 standard for frequency of strain measuring was followed.

Prior to measuring gage lengths on the specimens, a reference bar measurement was recorded for the 8.0-in. gage length. Three gage measurements were taken from each gage length, and an average gage length were recorded from these measurements. The initial elastic strain required gage length measurements before (t_{14hrs} , t_{70hrs}) and immediately following (t_{14+hrs} , t_{70+hrs}) the applied load. Calculating the initial elastic strain was done as in equation 3.1 where 8.0-in. is to be taken as the initial gage length. The following shrinkage strain calculations will require the new gage lengths after the load has been applied to the specimens and will be calculated as in equation 3.2.

3.1

$$\varepsilon_{initial} = \frac{(gage_{after} - gage_{before})}{8.0 + (ref_{bar} - gage_{before})}$$

Where:

$\varepsilon_{initial}$ = initial elastic strain

$gage_{after}$ = gage reading after applied load

$gage_{before}$ = gage reading before applied load

ref_{bar} = reference bar reading for 8.0in on Whittemore strain gage

3.2

$$\varepsilon_{4hr} = \frac{(gage_{4hrs} - gage_{after})}{8.0 + (ref_{bar} - gage_{after})}$$

Where:

$$\begin{aligned}\varepsilon_{4hr} &= \text{strain 4 hours from applied load} \\ gage_{4hrs} &= \text{gage reading 4 hrs after applied load}\end{aligned}$$

The ASTM C512 standard outlines the strain measurement intervals for calculating creep in normal NSC, however the rapid strength gain in the first 24 hours for UHPC required additional strain measurements to be acquired between the 4 hour and 24 hour strain measurements recommended in ASTM C512 standard. At least one additional early-age gage length reading was recorded (approximately at 14 hours after applied load) for each curing regime. Additional strain measurements were taken immediately prior to, and following the thermal cure. These measurements helped determine the direct affect of the thermal treatment on the specimen's creep response. The specimens were monitored for a period of 24-28 days following the creep load application, and 17-24 days following the thermal cure.

3.5.4 Modulus of Elasticity Checks

A comparison of values for the UHPC modulus of elasticity found in this research were evaluated with previous findings on modulus of elasticity values for UHPC, as well as the ACI formulas for both NSC and HSC. Equation 3.3 provides the modulus of elasticity calculation used in this research.

$$E = \frac{F * (L_1)}{A * (\Delta L)} \quad 3.3$$

Where:

$$\begin{aligned}E &= \text{modulus of elasticity} \\ F &= \text{initial applied force in kips} \\ L_1 &= \text{the initial gage length} \\ \Delta L &= \text{the change in gage length after initial applied load}\end{aligned}$$

The modulus of elasticity calculations performed in this research were performed as a confidence check with the models discussed in section 3.6.4. As previously noted, the data calculated from the stress and strain values in this research should not be considered as an accurate method of predicting the elastic modulus of UHPC; the testing was not consistent with the ASTM C469 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, but rather results are presented to give a general level of confidence for checking.

3.6 Data Acquisition

The data acquisition for this research was used to verify that a constant load range could be maintained through all stages of the creep test. The ambient conditions of the creep frame storage room and thermal curing chamber were also monitored through this research. The data acquisition in the creep frame storage room was collected using an EXTECH[®] instruments data-logger. An air conditioner, humidifier, and dehumidifier work in unison to maintain the storage conditions of the ASTM-C512 standard. The pre-steam and thermal curing chambers will require water heating elements, controlled by a Love Controls[®] 16A temperature/process control units to ramp up and hold the temperature for the recommended curing durations.

3.6.1 DPM-3 Digital Panel Mount Meter

The DPM-3 digital panel mount meters installed on these creep frames communicate with the CLC-200K (200 kip capacity) load cell. The DPM-3 meters were daisy-chained together allowing all six of the creep frames to be maintained on a single computer system through DASyLab software.

3.6.2 DASYLab Software

The software chosen to record the compressive force applied to the creep frames was DASYLab version 11.0. This software was able to record a load value read by the DPM-3 digital panel mount meter for each of the six creep frames on 8 second intervals. When the load dropped below a preset value, the air pumps turned on pumping air pressure to the pneumatic/hydraulic pumps which pump hydraulic fluid to maintain a specific load level on the specimens. This software verified that a consistent load could be maintained on the specimens throughout the duration of the test.

4 Results

4.1 Introduction

Five curing regimes were investigated in this research with specimens undergoing compressive creep and companion shrinkage testing (a detailed explanation of each curing regime in section 3.4.

- *AMC, ambient curing regime*
- *SST, standard thermal curing regime*
- *PST, pre-steam/standard thermal curing regime*
- *PSD, pre-steam/delayed thermal curing regime*
- *PDD, pre-steam/double delayed thermal curing regime*

The creep and shrinkage results for each curing regime are presented in terms of strain calculations for each specimen. All specimens tested in these experiments were cast in horizontal steel molds to ensure plane and parallel end requirements. The horizontal steel molds required no cutting or end grinding of the specimens which reduced the delay between demolding and compressive loading of the specimens. Each specimen was instrumented with three gage points measuring 8.0-in. gage lengths. The results presented here for each cylinder are an average of these gage strain measurements for each specimen. The specimens were loaded at the design recommended compressive stress of 14 ksi before undergoing a thermal or ambient air cure. The specimens were either allowed to air cure at ambient conditions before reaching 14 ksi, or a pre-steam cure was implemented to accelerate this early strength.

4.2 Compressive Strength Gain Results

The reproduction of the early-age compressive creep gain studies were performed to establish a timeline for loading the specimens. A pre-steam and ambient air cure was performed on horizontally cast UHPC specimens until the “required release strength” of 14 ksi was reached.

4.2.1 Ambient Cure Compressive Strength Gain Results

The ambient air cured batch study (ABC-1C) was conducted on specimens allowed to cure at ambient conditions of $73^{\circ}\text{F} \pm 3.5^{\circ}\text{F}$ and 50% relative humidity. A total of 12 horizontally cast specimens were used. The batch was completed in Benedict Lab at 5:00PM on February 4th, the batching and mixing information can be found in Appendix B. Using horizontal steel molds for compression testing allowed for plane and parallel ends on every cylinder per ASTM C617 standard, therefore no time was wasted due to the need for sulfur capping. Prior to testing the UHPC specimens, four diameter readings and four length readings were recorded to calculate an average for each. Diameter averages would vary slightly due to the slot running the length of the mold, in which the molds were filled with the UHPC. The actual diameter and length readings can be seen in Appendix C. Test specimens were randomly selected with the first test occurring 49 hours (6:00PM February 6) after the original batch completion time, yielding 9.9 ksi, a much lower stress reading than the target compressive strength goal. Testing the remaining 11 specimens resumed the following day (8:00AM February 7) and were tested every half hour from 62.5 hour to 66 hours, then 67 hours and 70.5 hours after the original batch completion time. Progressive strength gain was observed in the specimens; however only the final test (4:30PM February 7) had a

compressive stress above the target value, at 14.4 ksi. The data collected from all the specimens can also be observed in Appendix C.

A linear trend line superimposed on the graph in Figure 4.1 illustrates the compressive strength gain over time. It was determined from this data that UHPC, when cured at ambient conditions, was expected to reach a compressive stress of 14 ksi at approximately 70 hours elapsed time from casting. Therefore, the two curing regimes involving an ambient cure prior to loading (AMC and SST) resulted in the application of creep loading at 70 hours from the casting time.

4.2.2 Pre-steam Cure Compressive Strength Gain Results

A graph of the pre-steam cure compressive strength gain results can be seen in Figure 4.2. The pre-steam compressive strength gain study (PSC-1C) was performed on specimens that were subjected to a steam cure prior to testing. Specimens were placed in a steam fed chamber which involved a 2 hour ramp up cycle from ambient air temperature (72°F) to 140°F with a relative humidity of 95%. A total of 11 horizontally cast specimens were used. The batch was completed in Benedict Lab at 5:00PM on January 31st, the batching and mixing information can be found in Appendix B. Specimens were randomly selected for compression testing beginning 14 hours (7:00AM February 1st) after the specimens were placed in the steam cure chamber. The first test (PSC-C1-14) had exceeded the target compressive strength of 14 ksi in 14 hours. The remaining specimens were then tested to failure in 1 hour increments until 10:00AM on February 1st, and in half hour intervals until 1:00PM. All the specimens were tested in order to identify a compressive strength

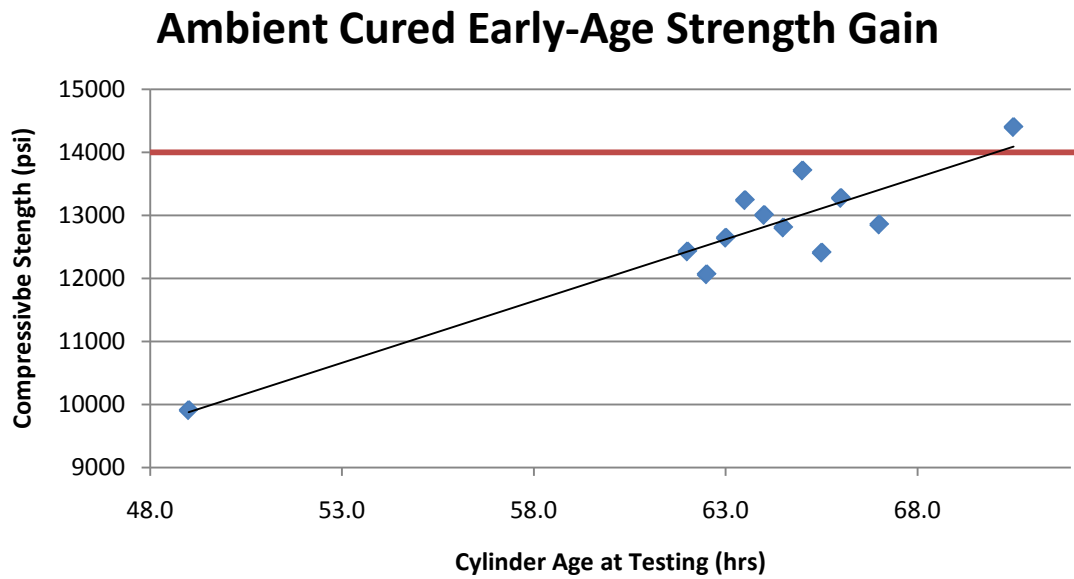


Figure 4.1 Ambient cure compressive strength gain study

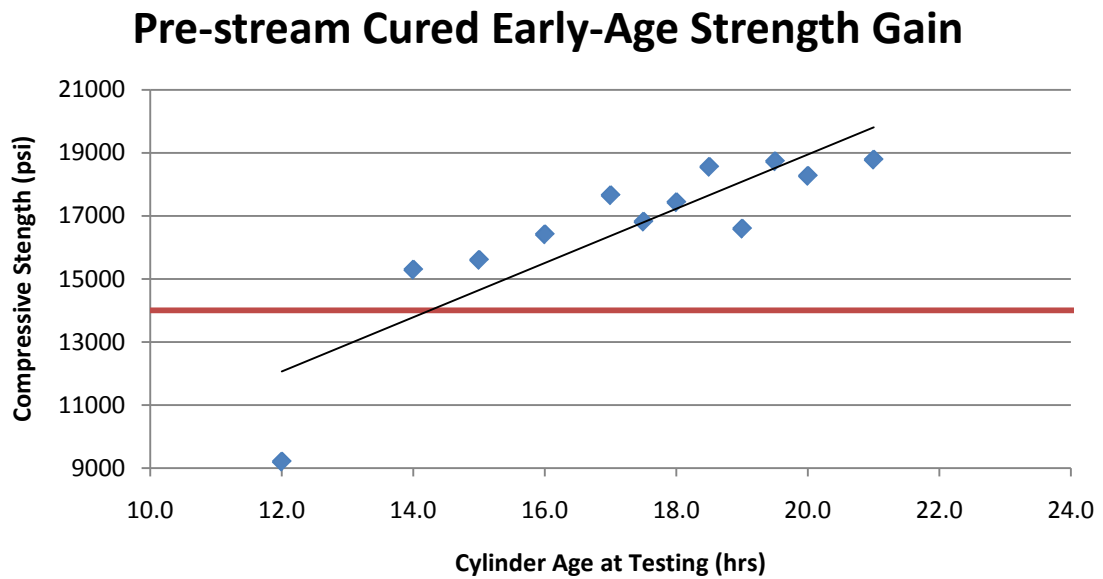


Figure 4.2 Pre-steam cure compressive strength gain study

gain trend in the pre-steam treated specimens. It was determined that with a linear trend line, the compressive strength could be extrapolated to locate the target compressive strength at 12 hours from the time of casting with a pre-steam cure.

A second pair of horizontal steel molds were used to cast cylinders (COMP-1 and COMP-2) from a UHPC batch occurring on May 17th, at 7:10PM. It is important to note that these specimens were acquired as extra UHPC from a batch occurring for other research at Michigan Tech, therefore only two specimens could be cast. These cylinders were subjected an identical pre-steam cure and were tested at 12 hours (7:10 AM May 18th) to failure. The average compressive strength of these specimens (9.2ksi) was much lower than the target value of 14 ksi. When the additional point was added to the data previously collected for early-age strength gain for the pre-steam specimens, it was determined that specimens subjected to the pre-steam treatment in this research reached a compressive strength of 14 ksi in 14 hours from the batch life. The data collected from all the specimens can also be observed in Appendix C.

4.3 Varying Curing Regimes Compressive Creep and Companion Shrinkage Data

Five curing regimes were tested during this research project. Each curing regime used two different compressive load levels to investigate the creep response of the UHPC. The determination of these load levels were discussed in section 3.2.4 and set as close to $0.6f'_{ci}$ and $0.2f'_{ci}$ as possible. In all scenarios the UHPC specimens were loaded in compression prior to the application of the full thermal treatment, and held under a constant compressive load for the duration of the study. All specimens were stored in

an ambient controlled room, when not undergoing a steam treatment, with storage conditions at a temperature of $73.5^{\circ}\text{F} \pm 3.5^{\circ}\text{F}$ with a relative humidity of $50\% \pm 4\%$.

4.3.1 Ambient Air Cure Data

The ambient air cure (AMC) batch was mixed and cast at 5:00 PM June 28th, 2011. The specimens were allowed to cure in an ambient controlled room at a temperature of $73.5^{\circ}\text{F} \pm 3.5^{\circ}\text{F}$, with a relative humidity of $50\% \pm 4\%$ for duration of 70 hours, as determined by the compressive strength gain studies. Specimens were demolded at 2:00 PM on July 1st, 2011 and given specimen identification. The specimens were weighed and measured in both diameter and length and initial gage lengths were recorded. The three shrinkage specimens were sealed with butylcaoutchouc coated aluminum tape, and the remaining six specimens were loaded into the two creep frames; AMC-C1-H, AMC-C2-H, AMC-C3-H were loaded in the low level creep frame of $0.2f'_{ci}$, and AMC-C4-L, AMC-C5-L, AMC-C6-L were loaded in the high level creep frame of $0.6f'_{ci}$. The reason the “-H” cylinders were loaded in the low level creep frame, and “-L” cylinders were loaded in the high level creep frame was due to a last minute data acquisition error. The data acquisition error occurred in DASYLab on the frame in which the “H” cylinders were loaded. Because the higher load level was more crucial to this research, it was applied to the cylinders loaded in the frame that was designated for the lower load; therefore the specimens subjected to the high load level could be monitored through DASYLab. For this curing regime the lower load level would not be monitored through DASYLab, instead readings were taken from the hydraulic pressure dial installed on the hydraulic hose between the pneumatic/hydraulic pump and the hydraulic jack.

Just prior to loading the specimens, three of the compressive samples were tested at an elapsed time of 72 hours (2 hour delay was due to demolding and measuring specimens prior to creep loading) to find that the compressive strength was an average of 12.2 ksi. This required reducing the load levels to 51.8 kips for the high load level, and 17.25 kips for the low load level to stay consistent with $0.6f'_{ci}$ and $0.2f'_{ci}$ loading scenarios. All of the specimens in the creep frame throughout this research were loaded at a rate of approximately 60 psi/sec over the duration of approximately 2 minutes and 40 seconds for the high and low load levels, respectively. The creep frames were allowed to stabilize for five minutes before the specimen gage lengths were measured again. For this initial measurement, an average of three gage length measurements was recorded to determine the initial elastic strain (consistent with all the curing regimes in this research). Gage lengths were measured on all specimens at 4 hours from loading per ASTM-C512 standard, and additionally at 14 hours to better define the early-age creep response. The initial creep and shrinkage data sheet and the daily creep and shrinkage data sheets can be seen in Appendix D.

For the AMC curing regime, an average initial elastic strain of $1269\mu\epsilon$ and $579\mu\epsilon$ were measured for the $0.6f'_{ci}$ and $0.2f'_{ci}$ load levels, respectively. The average 28 day total strains after loading (not including initial elastic strains) and shrinkage strains measured in this research, $1438\mu\epsilon$, $693\mu\epsilon$ and $380\mu\epsilon$ for the high and low load levels and shrinkage strain, respectively. Figure 4.3 plots the average total strain for each load level and the shrinkage specimens. Each data point represents the average of nine readings (three measurements on three cylinders).

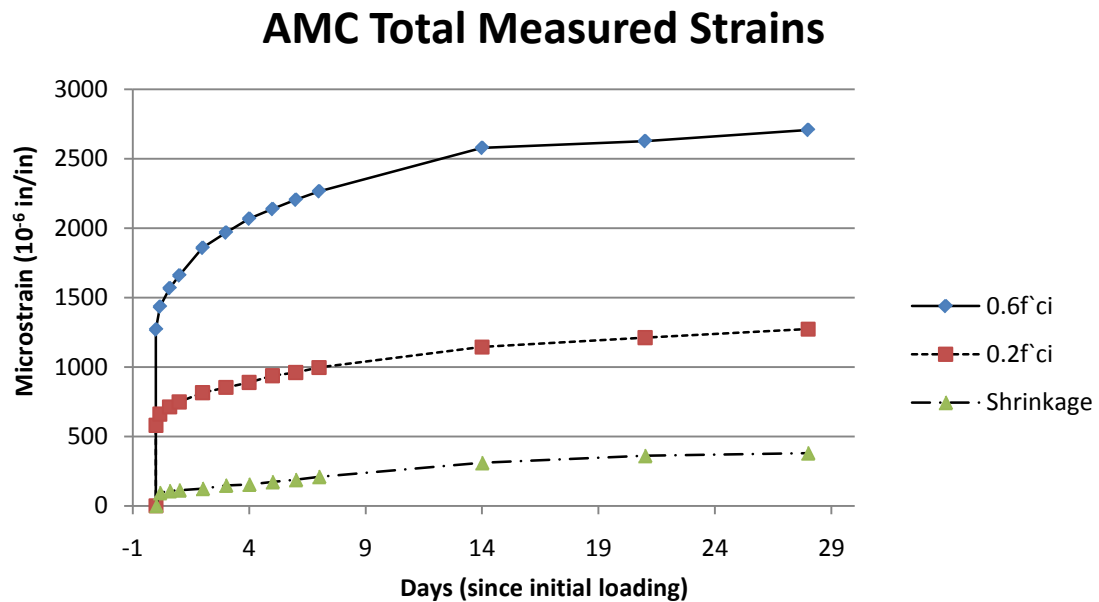


Figure 4.3 AMC total measured strains

Figure 4.3 is adapted from the strain measurements of each of the three cylinders subjected to the high load level, low load level and shrinkage scenarios, including the initial elastic strain recordings. To better understand the data scatter between the individual cylinders, Figure 4.4 provides the individual measurements of the data, which plots an average total strain after loading of the three gage length measurements present on each cylinder. These plots (which do not include the initial elastic strain) and the individual strain measurements for all five curing regimes can be seen in Appendix D - Creep and Shrinkage Data.

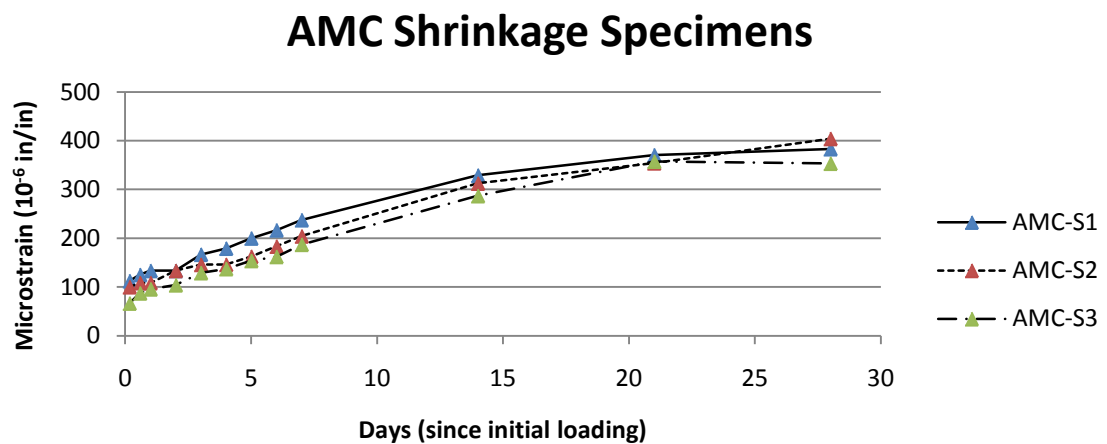
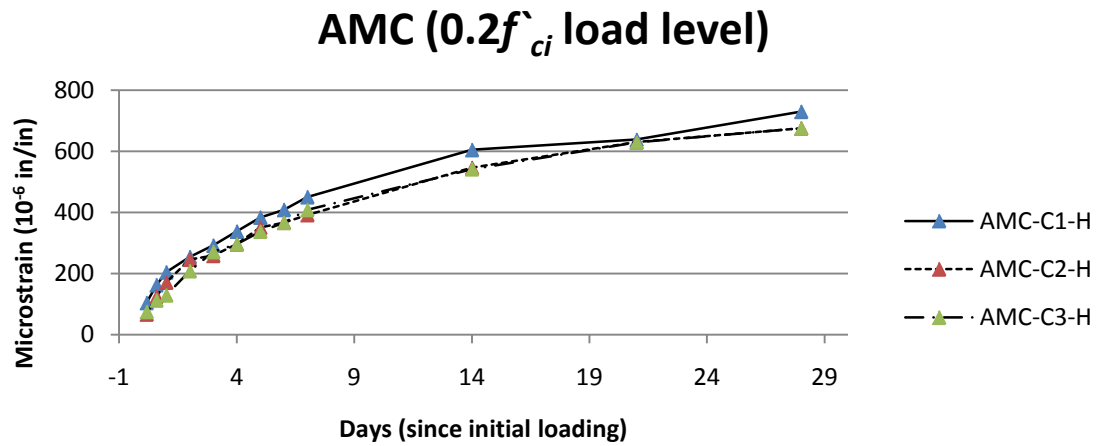
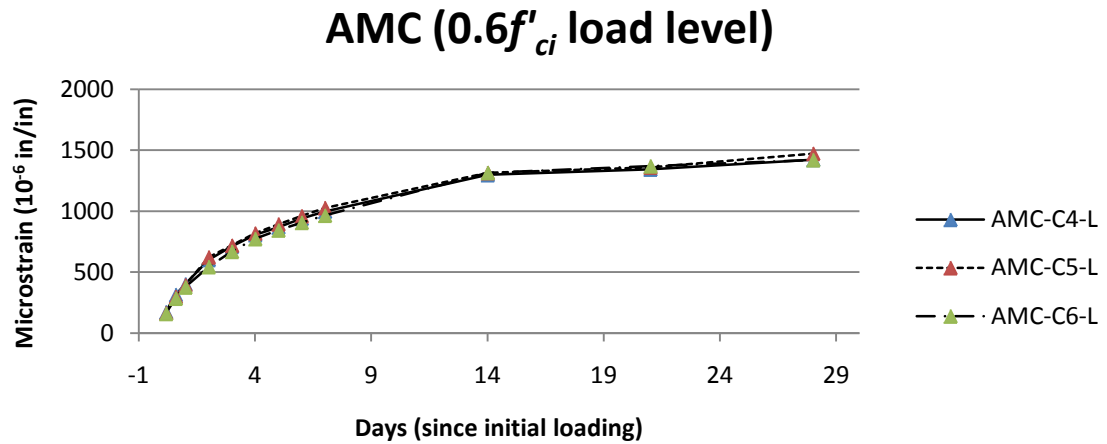


Figure 4.4 AMC individual creep and shrinkage strains

4.3.2 Standard Thermal Cure Data

The SST batch was mixed and cast at 4:01 PM June 21st, 2011. Similar to the AMC curing regime, specimens were allowed to cure in an ambient controlled room for a duration of 70 hours, as determined by the compressive strength gain studies, before being loaded.

Specimens were demolded at 1:01 PM on June 24th, 2011 and given specimen identification. The weight dimensions and initial gage length were recorded for each specimen as described in the AMC section. SST-C1-H, SST-C2-H, SST-C3-H were loaded in the high level creep frame of $0.6f'_{ci}$, and SST-C4-L, SST-C5-L, SST-C6-L were loaded in the low level creep frame of $0.2f'_{ci}$. This loading scenario would remain consistent for the remaining curing regimes. Figure 4.5 graphs the average increasing total strain (including elastic strain) for the SST specimens with respect to time for the specimens subjected to the high load, low load and shrinkage specimens. Each data point represents the average of nine readings, as with the AMC specimens. The elastic strain induced by the creep loading is shown by the vertical jump at day zero.

Prior to loading, the compressive strength at 72 hours (two hour delay was due to demolding and measuring the specimens before loading) was determined through compressive testing as 13.3 ksi. However, the applied load levels were not reduced for this loading scenario resulting in slightly higher and new load levels of $0.63f'_{ci}$ and $0.21f'_{ci}$. After the initial gage measurements were recorded, the loaded creep frame and shrinkage specimens were moved into the custom creep frame curing chamber where the specimens were subjected to a thermal cure of 194°F (90°C) at 95% RH for a

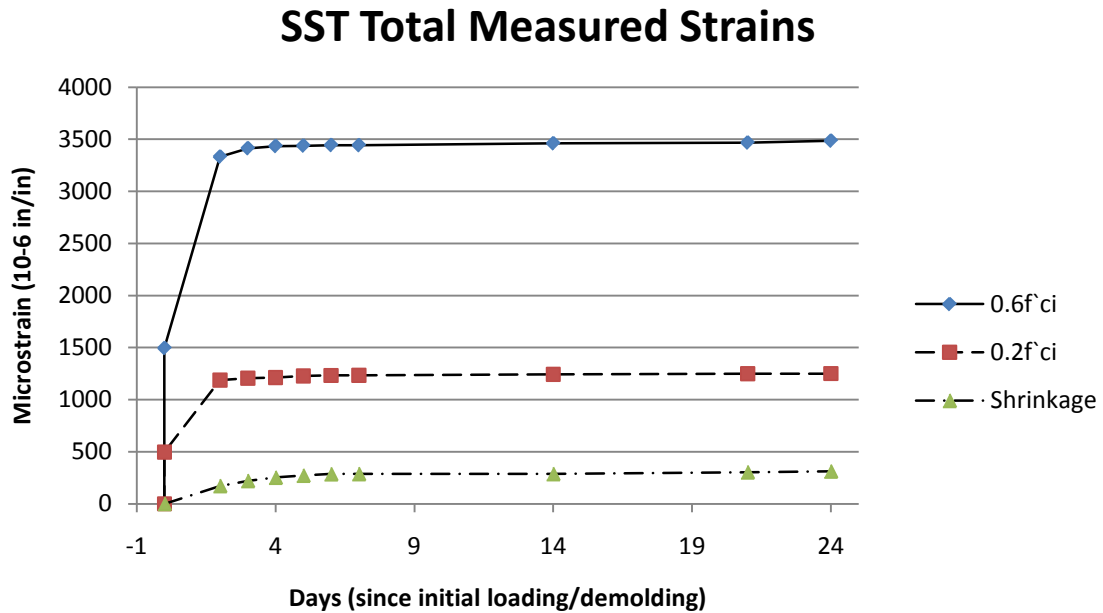


Figure 4.5 SST total measured strains

duration of 48 hours. Immediately following the recording of the length readings, and the creep frames were placed in the climate controlled room for the duration of the creep study. The initial creep and shrinkage data sheet and the daily creep and shrinkage data sheets can be seen in Appendix D. Gage measurements continued in accordance with the ASTM-C512 standard, with one additional reading recorded immediately prior to unloading the specimens at 24 days. Because of the timeframe in this research, creep frames A1-A2 and B1-B2 were used for two curing regimes, requiring a limited, but sufficient early-age creep study of the SST, and PST curing regimes.

For the SST curing regime, average initial elastic strains of $1403\mu\epsilon$ and $466\mu\epsilon$ were measured for the $0.6f'_{ci}$, and $0.2f'_{ci}$ load levels, respectively. The 24 day average total strain (minus initial elastic strains) and shrinkage strains measured in this

research ($1991\mu\epsilon$, $755\mu\epsilon$ and $313\mu\epsilon$) for the high and low load levels and shrinkage strain, respectively.

4.3.3 Pre-Steam /Thermal Cure Data

The PST batch was mixed and cast at 8:55 PM June 16th, 2011. Following the casting, the specimens were placed in a curing chamber for the pre-steam treatment (140°F (60°C) at 95% RH) for 14 hours to reach the target strength of 14 ksi, as determined by the compressive strength gain studies. Specimens were demolded at 11:00 AM on June 17th, 2011 and given specimen identification. The weight dimensions and initial gage length were recorded for each specimen as described in the previous section. Just prior to loading the specimens, three of the compressive samples were tested at an elapsed time of 16 hours to find a compressive strength of 13.8 ksi. This required reducing the load levels to 58.6 kips, and 19.5 kips to stay consistent with $0.6f'_{ci}$ and $0.2f'_{ci}$ loading scenarios. As with the SST curing regime, after the initial gage readings were recorded, the loaded creep frame and shrinkage specimens were moved into the custom creep frame curing chamber. Immediately following the thermal treatment, gage length readings were recorded, and the creep frames were placed in the climate controlled room for the duration of the creep study. The initial creep and shrinkage data sheet and the daily creep and shrinkage data sheets can be seen in Appendix D.

For the PST curing regime, an average initial elastic strain of $1502\mu\epsilon$ and $573\mu\epsilon$ were measured for the $0.6f'_{ci}$, and $0.2f'_{ci}$ load levels, respectively. The average 24 day total strains (minus initial elastic strains) and shrinkage strains measured in this research ($1955\mu\epsilon$, $611\mu\epsilon$ and $303\mu\epsilon$ for the high and low load levels and shrinkage

strain, respectively). Figure 4.6 graphs the average increasing strain with respect to time for the specimens subjected to the high load, low load and shrinkage.

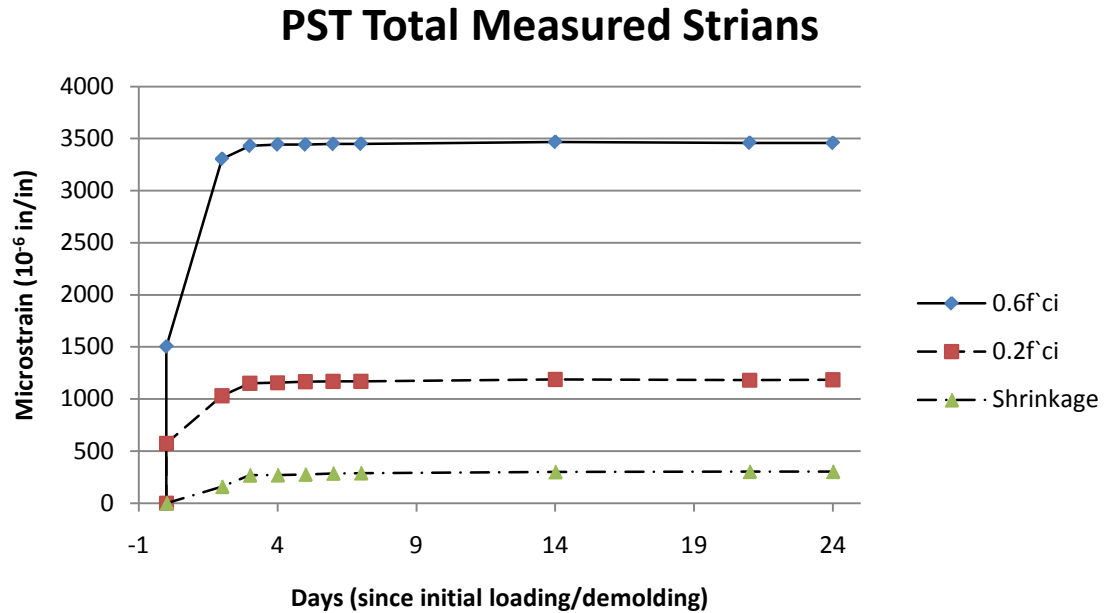


Figure 4.6 PST total measured strains

4.3.4 Pre-steam/Delayed Thermal Cure Data

The PSD batch was mixed and cast at 8:00 PM July 18th, 2011. Similar to the PST specimens, the PSD curing regime required subjecting the specimens to the pre-steam treatment, however the full thermal treatment was delayed 3 days. Figure 4.7 graphs the average increasing strain with respect to time. Specimens were demolded at 10:00 AM on June 19th, 2011 and given specimen identification. The weight dimensions and initial gage length were recorded for each specimen as described in previous sections. Prior to loading the specimens, an average compressive strength of 13.6 ksi was determined at 16 hours from demolding. This required reducing the load levels to

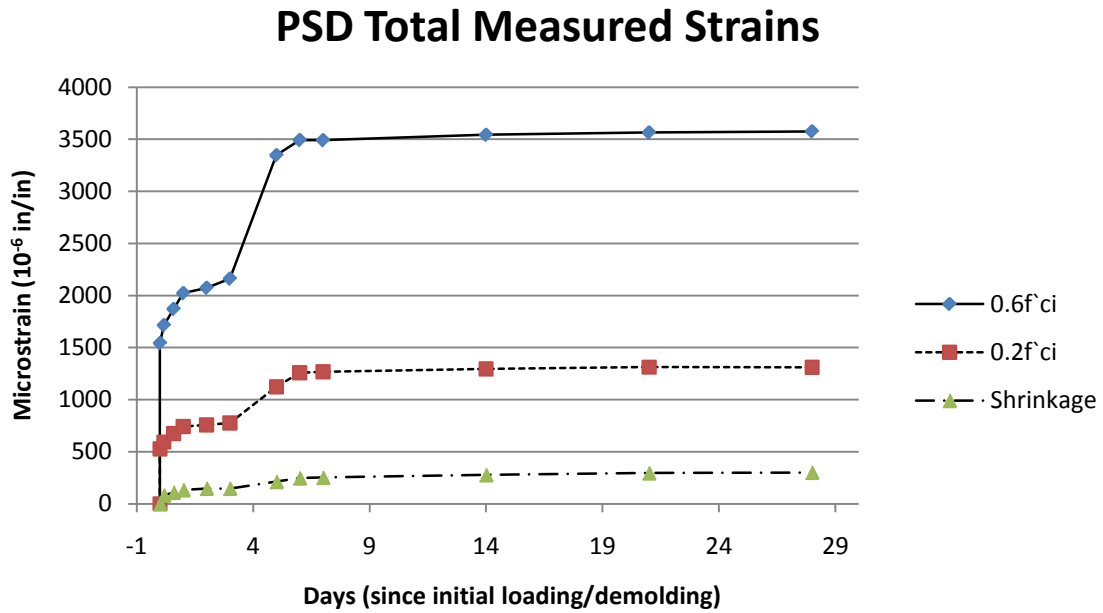


Figure 4.7 PSD total measured strains

57.8 kips, and 19.3 kips to stay consistent with $0.6f'_{ci}$ and $0.2f'_{ci}$ loading scenarios. Gage lengths were measured on all specimens at 4 hours from loading per ASTM-C512 standard, and additionally at 14 hours to better define the early-age creep response. The initial creep and shrinkage data sheet and the daily creep and shrinkage data sheets can be seen in Appendix D.

For the PSD curing regime an average initial elastic strain of $1542\mu\epsilon$ and $526\mu\epsilon$ were measured for the $0.6f'_{ci}$, and $0.2f'_{ci}$ load levels, respectively. The PSD specimens were stored in the ambient controlled room for a period of 72 hours, five strain measurements were recorded after the initial applied load for this 72 hour duration, per the ASTM-C512 standard. Seventy two hours after the applied load, the PSD specimens were moved to the custom built creep frame curing chamber to undergo a 48 hour thermal treatment (194°F (90°C) at 95% RH). After the specimens were

removed from the curing chamber, gage measurements were recorded and the specimens were returned to the ambient controlled room for the duration of the study. The last total strains (minus initial elastic strains) and shrinkage strains measured in this research, $2034\mu\epsilon$, $785\mu\epsilon$ and $301\mu\epsilon$ for the high and low load levels and shrinkage strain respectively, occurred at 28 days (August 16, 2011) from the time of initial time of loading.

4.3.5 Pre-steam/Double Delayed Thermal Cure Data

The PDD batch was mixed and cast at 7:00 PM July 12th, 2011. Similar to the PST and PSD specimens, the PDD curing regime required subjecting the specimens to the pre-steam treatment, prior to a full thermal treatment. Specimens were demolded at 9:00 AM on June 13th, 2011 and given specimen identification. The weight dimensions and initial gage length were recorded for each specimen as described in previous sections. The compressive strength at 16 hours was found to be 13.4 ksi, which required reducing the load levels to 56.9 kips, and 19.0 kips to stay consistent with $0.6f'_{ci}$ and $0.2f'_{ci}$ loading scenarios. The initial creep and shrinkage data sheet and the daily creep and shrinkage data sheets can be seen in Appendix D.

Figure 4.8 graphs the average increasing strain for the PDD specimens with respect to time for the specimens subjected to the high load, low load and shrinkage specimens. For the PDD curing regime an average initial elastic strain of $1451\mu\epsilon$ and $557\mu\epsilon$ were measured for the $0.6f'_{ci}$, and $0.2f'_{ci}$ load levels, respectively. Similar to the PSD specimens, the PDD specimens were stored in the ambient controlled room for a period of 11 days (approximately 264 hours). Ten strain measurements were recorded after the initial applied load for this 264 hour duration, per the ASTM-C512 standard.

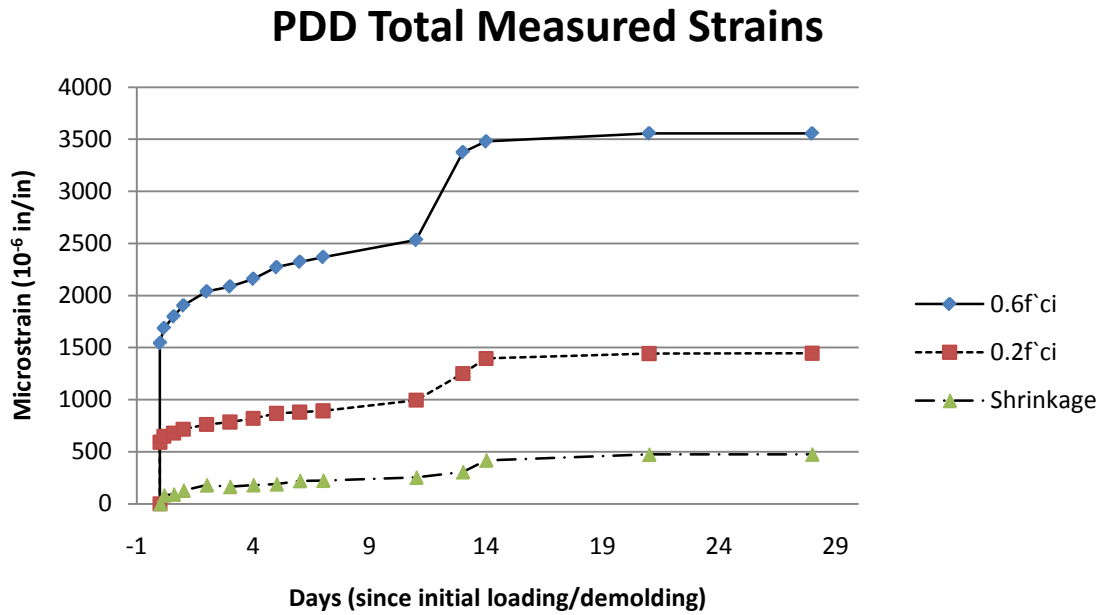


Figure 4.8 PDD total measured strains

Eleven days after the applied load, the PDD specimens were moved to the custom built creep frame curing chamber. After the specimens were removed from the curing chamber, gage measurements were recorded and the specimens were returned to the ambient controlled room for the duration of the study. The last total measured strain (minus initial elastic strains) and shrinkage strains measured in this research ($2012\mu\epsilon$, $879\mu\epsilon$ and $475\mu\epsilon$ for the high and low load levels and shrinkage strain, respectively) occurred at 28 days (August 10, 2011) from the time of initial time of loading.

5 Discussion

5.1 Review of Data Collection

The data collected herein covers the initial findings of the early-age creep effects of UHPC under a compressive load through varying curing regimes. To isolate the creep strains for each curing scenario, the elastic strain and the shrinkage strains must be removed from the total measured strain. For example, the total measured strain presented in section 4.3.1 for the ambient cured specimens under the high load level, $0.6f'_{ci}$, at 28 days was $2707\mu\epsilon$, the elastic strain was $1269\mu\epsilon$, and the shrinkage strain was $380\mu\epsilon$. Therefore, the creep strain at 28 days for this scenario was $1058\mu\epsilon$. Table 5.1 lists the average isolated creep strains for each curing regime and compressive creep load level.

Table 5.1
Average initial elastic and 24-28 day strain values for each curing regime.

Curing Regime	f'_{ci}/f'_c	Elastic Strain	24-28 day Creep Strain Measurement	C_{ct}
AMC	0.60	1269	1058	0.83 (1.27)*
	0.20	579	313	0.54 (0.80)*
SST	0.63	1494	1678	1.12
	0.21	496	442	0.89
PST	0.60	1316	1653	1.26
	0.20	573	309	0.54
PSD	0.60	1542	1727	1.12
	0.20	526	491	0.93
PDD	0.60	1543	1537	1.00
	0.20	591	404	0.68

* predicted at one year

The creep coefficients are calculated in Table 5.1 by dividing the measured 24-28 day creep strains by the initial creep strains ($\epsilon_{28}/\epsilon_{\text{initial}}$) found for each curing regime. The average creep coefficient (C_{ct}) for specimens subjected to a thermal cure for the $0.6f'_{ci}$ load level was 1.12 and 0.76 for the $0.2f'_{ci}$ load level. The data in Table 5.1 only considers the effects of creep by subtracting the shrinkage values found for each curing regime from the 24-28 day creep strain measurements.

5.2 Effects of Ambient Cure

The isolated creep strains collected for the ambient cured specimens were fit to a logarithmic function for the high load level and low load level specimens. The models can be seen in Figure 5.1. The logarithmic functions are plotted along with curves for each data series only looking at the creep strains in excess of the initial elastic strain due to loading, and the shrinkage strains removed. This type of function best fit the

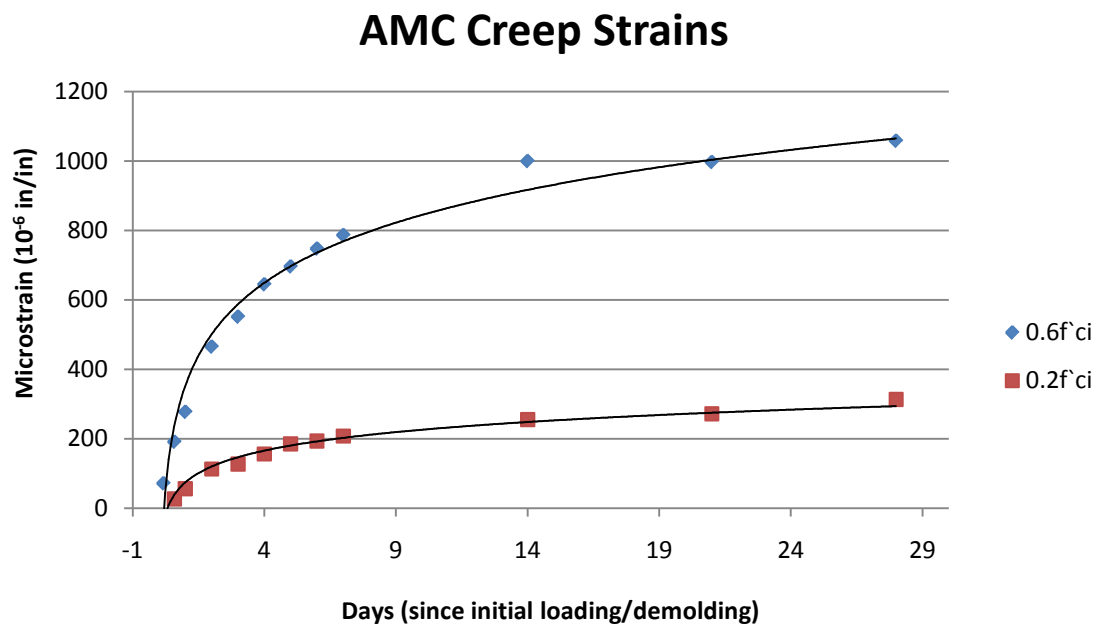


Figure 5.1 AMC creep strain results

data produced in this research and the function reaches an asymptotic value, as would be expected due to sustained loading, which can be used to predict a one year creep coefficient for the AMC specimens.

Equation 5.1 is the logarithmic relationship that best fit the ambient cured specimens subjected to the high stress level of $0.6f'_{ci}$. This relationship fits the early-age compressive creep strains closely, and predicts creep strain at 360 days of $1610\mu\epsilon$. The creep strains rapidly increase in the first week of applied loading and the rate of creep decreases in the following weeks. This prediction is almost identical to Graybeal's calculated $1600\mu\epsilon$, however the specimen ages and dimensions are not comparable.

5.1

$$\epsilon_x = 213.7 * \ln(x) + 352.5$$

5.2

$$\epsilon_x = 65.88 * \ln(x) + 74.1$$

Where:

$$\begin{aligned} \epsilon_x &= \text{predicted strain, } \mu\epsilon \\ x &= \text{time in days} \end{aligned}$$

Equation 5.2 is similar to equation 5.1, but represents the best fit logarithmic curve for the lower $0.2f'_{ci}$ load level. Using this equation, the predicted 360 day ultimate creep strain for the $0.2f'_{ci}$ load level best yields a value of $468\mu\epsilon$. No research-to-date has subjected UHPC to compressive stress as low as $0.2f'_{ci}$ for a duration of 360 days to compare the validity of this relationship.

Using the predicted values for the one year creep strains on the ambient cured (AMC) specimens, a predicted creep coefficient of 1.27 and 0.80 are calculated for the $0.6f'_{ci}$ and $0.2f'_{ci}$ load levels, respectively. These creep coefficients are comparable to previous research found by Graybeal (2006) at 0.78, SETRA (2002) 0.80, JSCE (2006) 1.20, and UNSW (2000) 1.20.

5.3 Effects of Pre-steam Treatment

The administration of a pre-steam cure (140°F (60°C) at 95% RH) was used in this research to mimic what would be expected at a precast/prestress plant in the U.S. conforming to current practices as described in section 2.1.3. This pre-steam treatment accelerates the compressive strength of UHPC to the target compressive strength of 14 ksi five times faster than an ambient cure. The pre-steam treatment had no affect effect on the 28 day creep coefficients for the curing regimes in this research.

5.4 Effects of Thermal Treatment

The effects of the thermal treatment on specimens under a compressive load were an important goal in this research. The following figures (Figure 5.2 and Figure 5.3) plot the average increasing strain against time for the three specimens tested in each curing regime. In these graphs, the initial elastic strain is neglected, and the shrinkage strains have been subtracted to plot only the creep strain measured in this research.

The creep data shown in Figure 5.2 for the specimens subjected to the $0.6f'_{ci}$ reveals that after a thermal cure was administered on the specimens, the strain increased up to approximately $1650\mu\epsilon$, with no significant additional strain occurring thereafter. Specimens subjected to an immediate thermal treatment (SST and PST) saw a rapid

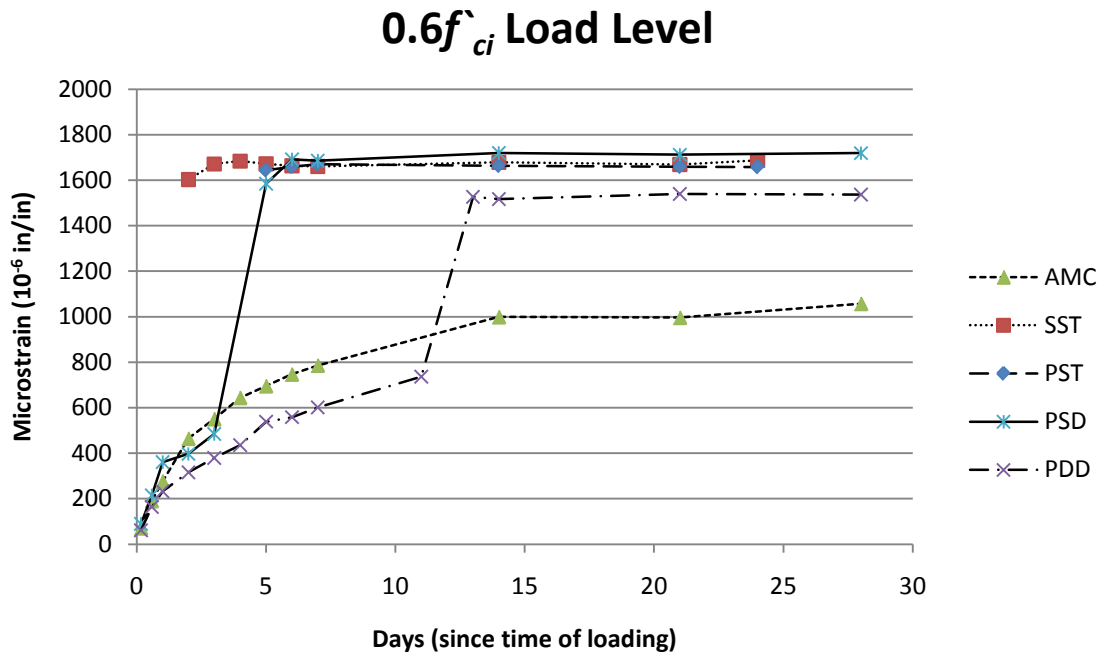


Figure 5.2 Average strain values for the $0.6f'_{ci}$ load level

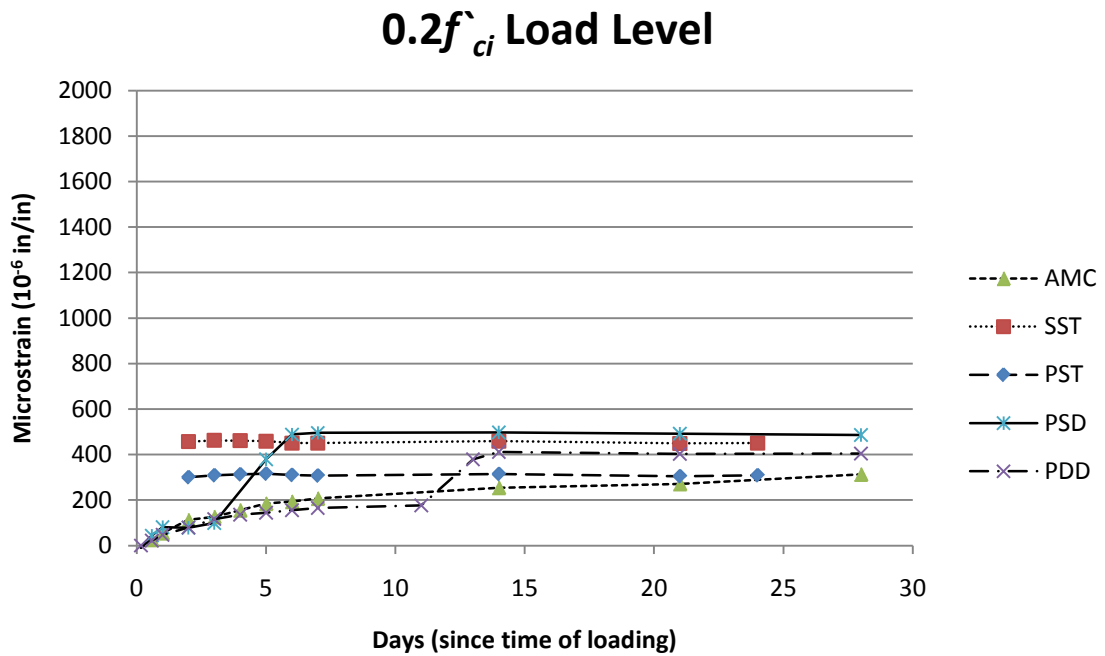


Figure 5.3 Average strain values for the $0.2f'_{ci}$ load level

average increase of 1655 $\mu\epsilon$ after removal from the custom built curing chamber. Specimens subjected to delayed treatments saw increases of 1121 $\mu\epsilon$ and 790 $\mu\epsilon$ for the PSD and PDD curing regimes, respectively. However, it is significant to note that the total creep strains for these specimens after the thermal treatment was 1593 $\mu\epsilon$ and 1527 $\mu\epsilon$ (PSD and PDD, respectively). In all curing regimes subjected to the thermal cure, the application of the thermal cure “locked in” the creep strains in the UHPC. Prior to the application of the thermal treatment on the PSD and PDD specimens, the creep strains followed ambient cure (AMC) baseline. The thermal cure “locked in” the creep strains to approximately 1550-1650 $\mu\epsilon$, with minimal changes in creep strains occurring thereafter. Table 5.2 provides the creep strain effects due to the thermal treatment for each curing regime.

Table 5.2
Measured creep strain before, during and after thermal treatment ($\mu\text{in/in}$)

		AMC	SST	PST	PSD	PDD
<i>0.6f_{ci}</i>	<i>Before TT</i>	--	0	0	472	737
	<i>During TT</i>	--	1666	1644	1121	790
	<i>After TT</i>	--	1666	1644	1593	1527
<i>0.2f_{ci}</i>	<i>Before TT</i>	--	0	0	103	176
	<i>During TT</i>	--	520	459	348	203
	<i>After TT</i>	--	520	459	384	355
Shrinkage Specimens	<i>Before TT</i>	--	0	0	147	253
	<i>During TT</i>	--	172	158	65	52
	<i>After TT</i>	--	172	158	212	305

Looking at specimen data for the lower load level for each of the curing regimes, more scatter in the results is observed. Similar to the higher load level, the strains occurring during the thermal treatment decreases as the specimens subjected to the delayed treatment increases (PSD and PDD curing regimes). The specimens with

delayed onset of a thermal treatment show increasing strains following the pattern of the ambient cured specimens before the thermal treatment is administered. In general, and independent of any pre-steam treatment, specimens that were thermally cured reach creep strains of 300-500 $\mu\epsilon$, and this strain was “locked in” and stable. The scatter in data is attributed to the low load level chosen for this research; higher load values produce more consistent creep data for UHPC.

5.5 Creep Coefficients

From the 28-day data presented in Table 5.1, the average creep coefficient (C_{ct}) for specimens subjected to a thermal cure found in this research for the $0.6f'_{ci}$ load level was 1.12 and 0.76 for the $0.2f'_{ci}$ load level, independent of when the thermal cure was applied, and independent of whether a pre-steam cure was used. The creep coefficients (C_{ct}) for the curing regimes subjected to a thermal cure calculated in this research are much higher than what was found by Graybeal 0.29 and, in all cases higher than the conservative values outlined in the recommendations by SETRA (2002) (0.20), JSCE (2006) (0.40), and UNSW (2000) (0.30). However, no research-to-date has looked at the creep strains of UHPC under a compressive load during a thermal cure. The specimens in this research were also loaded in compression at a lower compressive strength (14 ksi), which reduced the modulus of elasticity of the specimens. This reduced modulus of elasticity would directly affect the creep coefficient of the *weaker* specimens tested in this research. It has been observed in this research, that the effects of the thermal cure on UHPC specimens under a compressive load increase the creep strains to an asymptotic value, “locking in” the creep coefficient.

5.6 Shrinkage Response

The companion shrinkage strains found in this research varied slightly among each curing regime (see Figure 5.4). The effect of the thermal treatment on the shrinkage specimens was minimal on the specimens subjected to delays. Considering thermally cured specimens only and neglecting PDD specimens, the shrinkage specimens reached an asymptotic value of approximately $310\mu\epsilon$ 14 days after casting (it is believed that the gage studs for the PDD shrinkage specimens may have been damaged during thermal curing, resulting in higher strain values). This value is much lower, $255\mu\epsilon$ less, than what Graybeal had found for untreated specimens; however the time frame for this research was much shorter than the 250 day study performed by Graybeal. This means that shrinkage strains, for untreated specimens, continue to increase beyond the 28 day time frame studied in this research.

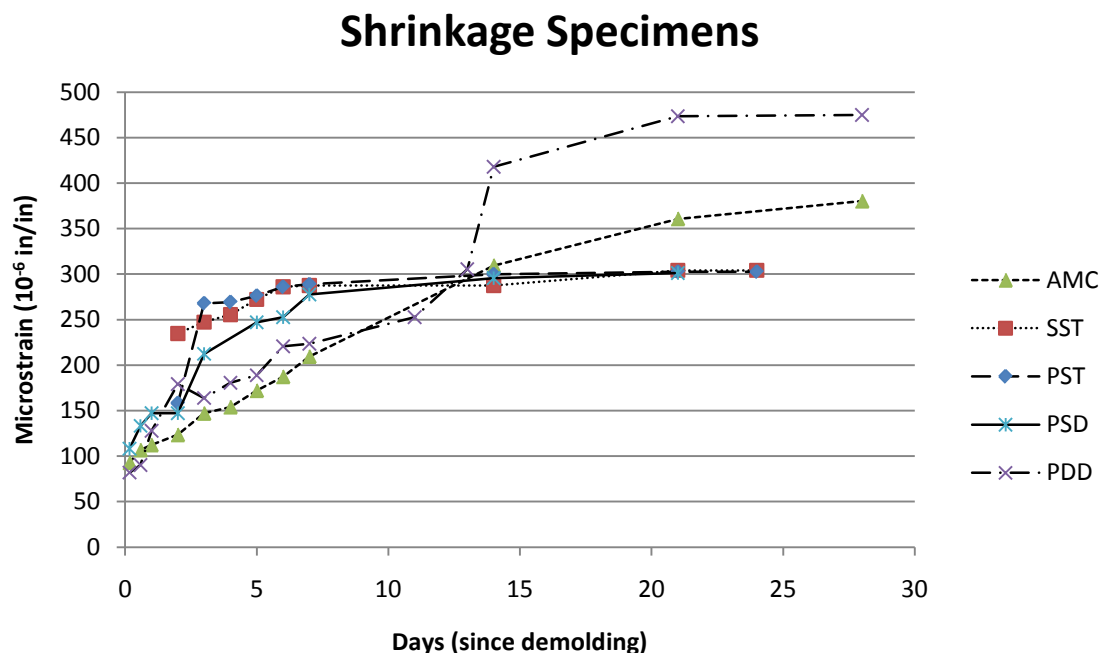


Figure 5.4 Average strain values for the shrinkage specimens

Figure 5.5 plots the average AMC shrinkage data found in this research and the best fit logarithmic function found in equation 5.3, predicting shrinkage strain at 360 days of $460\mu\epsilon$. When compared to Graybeal's value of $555\mu\epsilon$, and Burkart and Müller's value of $300\mu\epsilon$ after 200 days, the value predicted in this research falls into the range of previous reported research.

5.3

$$\epsilon_x = 58.7 * \ln(x) + 122$$

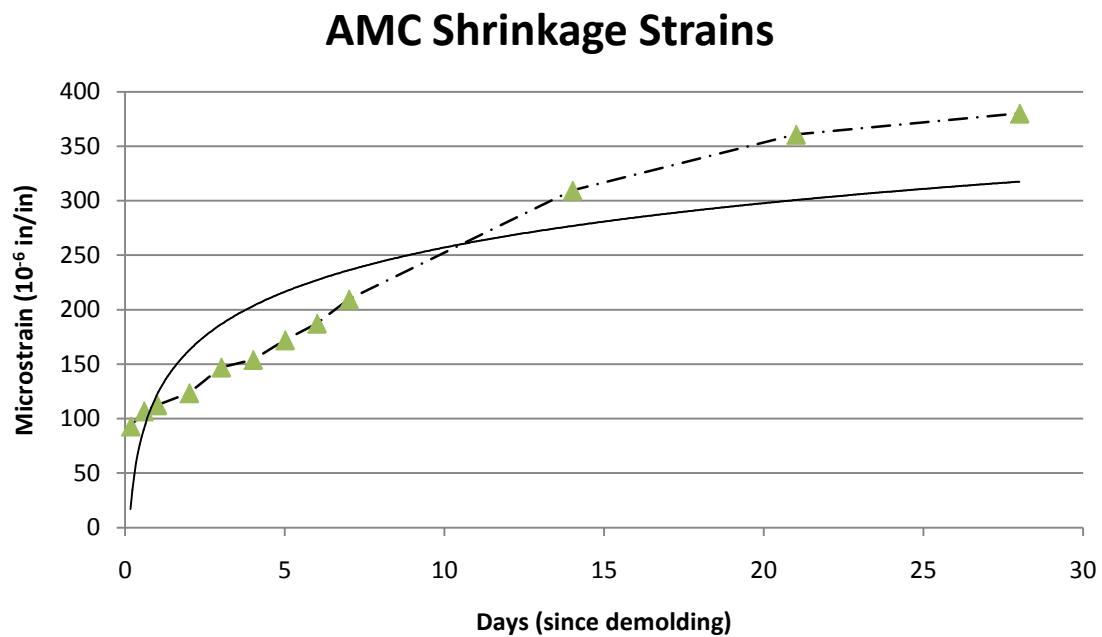


Figure 5.5 AMC shrinkage strains

5.7 Modulus of Elasticity

Calculations of the modulus of elasticity for each of the curing regimes was performed and compared to previous models for UHPC and high strength concretes. This comparison verifies that data presented in this research falls into the range of previous studies focused on creating a model for the modulus of elasticity for UHPC. However, the modulus of elasticity in this research only considered the initial strain

measurements before and after the applied load and was not consistent with the ASTM C469 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

Table 5.3 summarizes the average modulus of elasticity for each curing regime, and Figure 5.6 plots the predicted modulus of elasticity based on the equations presented in section 2.3. The modulus of elasticity for each curing regime was calculated using equation 3.3. A detailed breakdown of the modulus of elasticity calculations for each specimen is included in Appendix E.

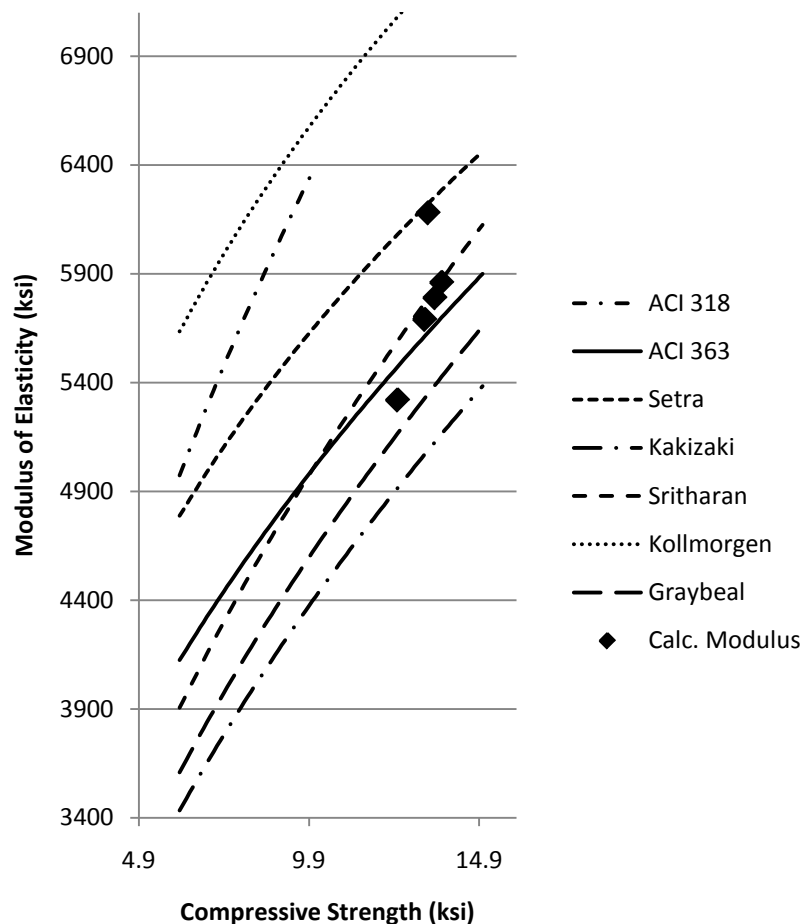


Figure 5.6 Compressive strength and modulus of elasticity relationships for UHPC

Table 5.3
Modulus of elasticity summary

Modulus of Elasticity Confidence Checks									
Curing Regime	Compressive Strength at Time of Loading (ksi)	Calculated Modulus (ksi)	<i>Modulus of Elasticity Models (ksi)</i>						
			ACI 318	ACI 363	SETRA (2002)	Kakizaki (1992)	Sritharan (2003)	Kollmorgen (2004)	Graybeal (2005)
PST	13.8	5860	7480	5700	6280	5160	5870	7310	5430
SST	13.3	5690	7340	5610	6200	5070	5770	7220	5330
AMC	12.2	5320	7030	5420	6030	4860	5520	7030	5100
PSD	13.6	5790	7420	5660	6250	5120	5830	7270	5380
PDD	13.4	6180	7370	5630	6220	5090	5090	7240	5350

The average modulus of elasticity calculated in this research falls with the values predicted by the models previous discussed. In most of the curing regimes investigated in this research, the average modulus of elasticity most closely follows the values predicted by the Sritharan et al.(2003) model for the compressive strength provided at the time of the initial loading. The ACI 318 relationship for NSC is not appropriate for compressive strengths higher than 10 ksi, but was included in the Figure 5.6 and Table 5.3 for comparison with the other models for UHPC. These predicted values corroborate with the calculations of modulus of elasticity found in this research and offer assurance to validity of the compressive creep testing performed.

6 Conclusions and Future Work

6.1 Conclusions and Recommendations

The data presented in this research provides the beginning framework for a more expansive compressive creep study on UHPC specimens under a thermal cure. This research looked at five curing conditions (see section 3.4), and was limited to one specimen size and two compressive creep load levels. The importance of this research was to characterize the early-age (28 day) creep and shrinkage characteristics of UHPC as it is thermally treated, under a compressive load. By doing so, this research found that the effects of the thermal cure “locked in” the creep and shrinkage strains independent of when the thermal cure was administered. In general, precast/prestressed plants would be able to produce several prestressed UHPC elements on differing timelines, then administer the thermal cure to all the elements together to save on energy costs, without having any significant effects on the “locked in” creep coefficient for thermally cured elements.

The following specific conclusions have been determined based on the data collected for specimens subjected to creep loading at a compressive strength of 14 ksi.

- Specimens loaded at $0.2f'_{ci}$ experienced an initial elastic strain of $553\mu\epsilon$ with negligible difference between ambient curing and pre-steam curing prior to loading, with an expected modulus of elasticity of 5800 ksi.
- Specimens loaded at approximately $0.6f'_{ci}$ experienced an initial elastic strain of $1382\mu\epsilon$ when subjected to an ambient cure prior to loading, and $1529\mu\epsilon$

when a pre-steam treatment (140°F at 95% RH) was administered prior to loading, with an expected modulus of elasticity, E_{ci} , of 5800 ksi.

- Delaying the thermal treatment for UHPC specimens under a compressive load has no significant effect on the final creep coefficient.
- When subjected to $0.2f'_{ci}$, specimens in this research were found to have an average compressive creep strain of $430\mu\epsilon$ after a thermal treatment, with no additional creep occurring up to 28 days, after a thermal cure.
- Specimens loaded at $0.6f'_{ci}$ reached a compressive creep strain reading of approximately $1645\mu\epsilon$ after a thermal treatment, with no additional creep occurring up to 28 days, after a thermal cure.
- The logarithmic equations (5.1 and 5.2) fit to data from the ambient cured (AMC) specimens predicted a one year creep coefficient of 1.27 and 0.80 for the $0.6f'_{ci}$ and $0.2f'_{ci}$ load levels, respectively. A one year shrinkage strain of $468\mu\epsilon$ was also predicted using a logarithmic equation fit to the shrinkage data.
- The creep coefficient was found to be greater on specimens under a compressive load during a thermal cure, as opposed to previous research of being thermally cured prior to loading. Average creep coefficient values of 1.12 and 0.76 were observed on specimens subjected to a thermal cure for the $0.6f'_{ci}$ and $0.2f'_{ci}$ load levels, respectively. The application of the thermal cure “locked in” the creep coefficient, as minimal strain changes were measured following the thermal cure.
- Shrinkage strains on the ambient cured specimens were projected to reach an asymptotic value of $460\mu\epsilon$, using equation 5.3, a best fit logarithmic function.

- Shrinkage strains on specimens subjected to the thermal cure measured in this research were found to stabilize at $310\mu\epsilon$ after curing and independent of when the thermal treatment was applied, with the exception of the PDD specimens.
- Shrinkage specimens in this research were not as affected by the thermal treatment as found by Graybeal's work (2006). The shrinkage was found to be approximately $310\mu\epsilon$ at 14 days with all the curing regimes in this research. Graybeal's work is a conservative model to the research performed herein.
- Previous research (equations 2.8-2.13) was used in this research to compare the elastic modulus of the specimens loaded in the creep frames. The data collected in this research should not be considered as an accurate method of predicting the elastic modulus of UHPC, but does provide a reasonable comparison to predicted elastic moduli.

6.2 Future Work

For each of the curing regimes tested herein, the data collection should follow the ASTM C512 standard for monitoring compressive creep on specimens for up to one year. This research was performed on a much shorter timeframe to get a preliminary assessment of creep and shrinkage response, and thus the ultimate creep and shrinkage strains may be underestimated in these findings.

Prior to the batching and casting of creep and shrinkage specimens, especially in precast plants, an early-age strength gain study should be performed to locate the target strength of 14 ksi. It is unclear if the results found from the PSC-1C and ABC-1C strength gain studies are reproducible. The reproduction of the early-age strength gain values found in this research differed from previous studies performed by Nyland

(2009). Creep and shrinkage values for compressive strengths for each curing regime were less than the target strength found in this research, requiring adjusting the compressive load levels to match the desired levels of $0.6f'_{ci}$ and $0.2f'_{ci}$. This variation in early-age strength may have to do with slight product variability from the manufacturer; in future work the UHPC used for the compressive strength gain studies should be from the same lot number as the UHPC used for the creep and shrinkage studies.

Though not employed in this research, implementing internal strain gages into the specimens may help verify manual gage length changes, and also provide strain measurements for the rapid strain increase experienced during a thermal cure.

Additional test specimens for each curing regime will help produce more data. Looking at only three shrinkage and creep specimens per load level limits the study to only one creep frame for each curing regime. Running identical curing regimes on multiple creep frames will produce much more usable data to draw more consistent conclusions. Additional data would give a basis for statistical analysis, rather than general observations cited herein.

In addition to several more specimens for data analysis, different specimen sizes should be considered to compare consistent data with previous findings. All tests performed herein used only 3.0-in. diameter specimens, which Burkart and Müller determined to have greater specific creep values when compared to 4.0-in. and 6.0-in. diameter specimens.

It would be appropriate to study specimen creep and shrinkage for UHPC specimens subjected to a pre-steam condition only, allowing for ambient cure to continue on the load specimens. This curing regime would also represent a scenario found in current U.S. precast facilities that are not yet mixing UHPC.

Further work needs to be done to include analysis methods to determine the impact of curing (as noted by creep and shrinkage) on prestress losses and ultimate deflections.

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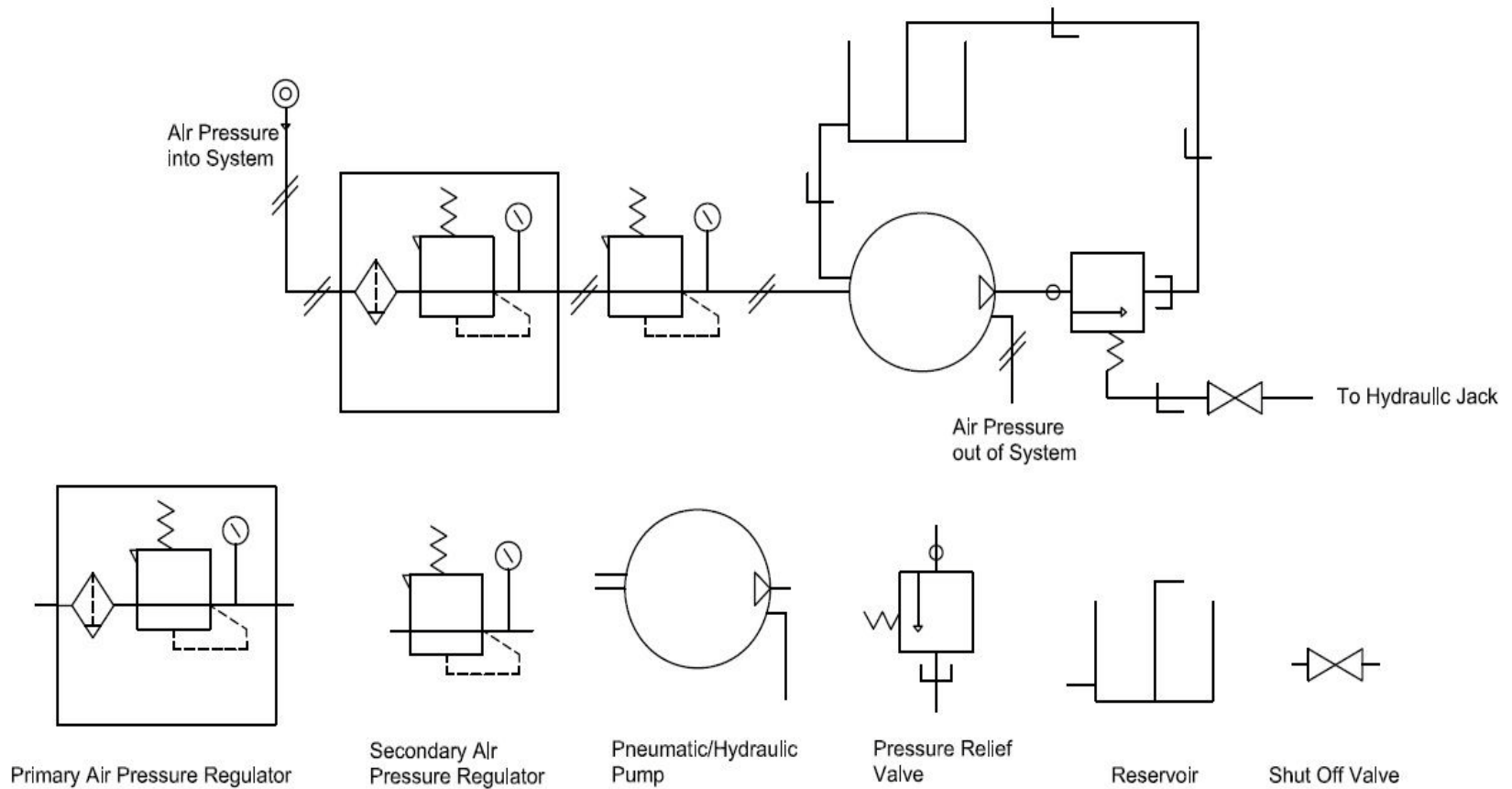
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Appendix A - Creep Frame Process Flow Diagram

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Appendix B - UHPC Mixing Data

Table B.1
PSC-1C mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

PSC-1C Compressive Strength Gain Study

Date:	Time:	Room Temp:	Room RH:
31-Jan-11	4:04 PM	72.3°F	21%

Estimated

(18L)

Actual Time

Temp (°F)

Amps

Time start mixing

Add water(w 1/2 SuperP) over 2mins

Increase to Speed 3 (mix 30 secs)

Increase to Speed 4 (mix 2min+1/2)

Increase to Speed 5 (mix 3min+1/2)

Increase to Speed 6 (mix 'til ball)

12 amps Turning Pt- Add SuperP

cont. mixing 'til motor evens out 6-7amps

Slow Speed 3-Add Fibers over 2mins

Slow Speed 1 (mix for 2 mins)

Flow Test (4 measurements) -**20 Blows** If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm

Before Blows

After Blows

0:00	0:00	70.5	
2:00	2:00	70	
4:15	4:15	69.5	
4:45	4:45	70	
7:15	7:45	70	
11:15	11:15	75.5	
--	24:30	79.5	12
--	26:00	84	7
26:30	26:00	86.5	
28:30	28:00	87	

		18L
Premix	(kg)	39.49
	(lb)	87.06
3000 NS	(kg)	0.54
	(lb)	1.19
Water	(kg)	2.32
	(lb)	5.11
Steel (2%)	(kg)	2.81
	(lb)	6.19

Lab Technicians

Jason

Miguel

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Table B.2
ABC-1C mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

ABC-1C Compressive Strength Gain Study

Date:	Time:	Room Temp:	Room RH:
4-Feb-11	3:55 PM	74.8°F	22%

Estimated
(18L)

Actual Time

Temp (°F)

Amps

Time start mixing

Add water(w 1/2 SuperP) over 2mins

Increase to Speed 3 (mix 30 secs)

Increase to Speed 4 (mix 2min+1/2)

Increase to Speed 5 (mix 3min+1/2)

Increase to Speed 6 (mix 'til ball)

12 amps Turning Pt- Add SuperP

cont. mixing 'til motor evens out 6-7amps

Slow Speed 3-Add Fibers over 2mins

Slow Speed 1 (mix for 2 mins)

Flow Test (4 measurements) -20 Blows If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm

Before Blows

After Blows

0:00	0:00	71.5	
2:00	2:00	69.5	
4:15	4:15	70.0	
4:45	4:45	70.5	
7:15	7:45	72.5	
11:15	11:15	79.0	
--	22:07	89.5	12
--	24:00	86.0	8
26:30	26:00	87.0	
28:30	28:00	87.0	

		18L
Premix	(kg)	39.49
	(lb)	87.06
3000 NS	(kg)	0.54
	(lb)	1.19
Water	(kg)	2.32
	(lb)	5.11
Steel (2%)	(kg)	2.81
	(lb)	6.19

Lab Technicians

Jason

Sarah

Table B.3
AMC mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

AMC Creep & Shrinkage Study

Date:	Time:	Room Temp:	Room RH:
28-Jun-11	2:57 PM	74.4°F	45%

Estimated
(18L)

Actual Time

Temp (°F)

Amps

Time start mixing
Add water(w 1/2 SuperP) over 2mins
Increase to Speed 3 (mix 30 secs)
Increase to Speed 4 (mix 2min+1/2)
Increase to Speed 5 (mix 3min+1/2)
Increase to Speed 6 (mix 'til ball)
12 amps Turning Pt- Add SuperP
*cont. mixing 'til motor evens out*6-7amps
Slow Speed 3-Add Fibers over 2mins
Slow Speed 1 (mix for 2 mins)
Flow Test (4 measurements) -**20 Blows** If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm

0:00	0:00	72.5	
2:00	2:00	73.0	
4:15	4:20	72.0	
4:45	4:45	73.5	
7:15	7:15	73.5	
11:15	11:15	74.0	
--	17:30	78.0	12
--	19:30	86.5	8
26:30	19:30	86.5	
28:30	21:30	88.0	

		18L
Premix	(kg)	39.49
	(lb)	87.06
3000 NS	(kg)	0.54
	(lb)	1.19
Water	(kg)	2.32
	(lb)	5.11
Steel (2%)	(kg)	2.81
	(lb)	6.19

Lab Technicians

Jason, Miguel,
Sarah

Before Blows

After Blows

180	180	190	190
220	225	230	225

Table B.4
SST mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

SST Creep & Shrinkage Study		Date:	Time:	Room Temp:	Room RH:																											
		21-Jun-11	3:01 PM	73.0°F	50%																											
Time start mixing Add water(w 1/2 SuperP) over 2mins Increase to Speed 3 (mix 30 secs) Increase to Speed 4 (mix 2min+1/2) Increase to Speed 5 (mix 3min+1/2) Increase to Speed 6 (mix 'til ball) 12 amps Turning Pt- Add SuperP <i>cont. mixing 'til motor evens out</i> 6-7amps Slow Speed 3-Add Fibers over 2mins Slow Speed 1 (mix for 2 mins) Flow Test (4 measurements) - 20 Blows If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm	Estimated (18L)	Actual Time	Temp (°F)	Amps																												
	0:00	0:00	71.0																													
	2:00	2:00	71.5																													
	4:15	4:15	70.0																													
	4:45	4:45	71.0																													
	7:15	7:15	71.5																													
	11:15	11:15	71.5																													
	--	17:40	78.5	12																												
	--	20:00	87.5	7.5																												
	26:30	20:00	88.0																													
28:30	22:00	88.0																														
					<table border="1"> <tr> <td></td> <td></td> <td>18L</td> </tr> <tr> <td>Premix</td> <td>(kg)</td> <td>39.49</td> </tr> <tr> <td></td> <td>(lb)</td> <td>87.06</td> </tr> <tr> <td>3000 NS</td> <td>(kg)</td> <td>0.54</td> </tr> <tr> <td></td> <td>(lb)</td> <td>1.19</td> </tr> <tr> <td>Water</td> <td>(kg)</td> <td>2.32</td> </tr> <tr> <td></td> <td>(lb)</td> <td>5.11</td> </tr> <tr> <td>Steel (2%)</td> <td>(kg)</td> <td>2.81</td> </tr> <tr> <td></td> <td>(lb)</td> <td>6.19</td> </tr> </table>			18L	Premix	(kg)	39.49		(lb)	87.06	3000 NS	(kg)	0.54		(lb)	1.19	Water	(kg)	2.32		(lb)	5.11	Steel (2%)	(kg)	2.81		(lb)	6.19
		18L																														
Premix	(kg)	39.49																														
	(lb)	87.06																														
3000 NS	(kg)	0.54																														
	(lb)	1.19																														
Water	(kg)	2.32																														
	(lb)	5.11																														
Steel (2%)	(kg)	2.81																														
	(lb)	6.19																														
					<table border="1"> <tr> <td colspan="2">Lab Technicians</td> </tr> <tr> <td colspan="2">Jason, Miguel, Sarah, Eric</td> </tr> </table>	Lab Technicians		Jason, Miguel, Sarah, Eric																								
Lab Technicians																																
Jason, Miguel, Sarah, Eric																																
	Before Blows	200	200	215	220																											
	After Blows	250	250	250	250																											

Table B.5
PST mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

PST Creep & Shrinkage Study

Date:	Time:	Room Temp:	Room RH:
16-Jun-11	7:54 PM	74.5°F	54%

Estimated
(18L)

Actual Time

Temp (°F)

Amps

Time start mixing

Add water(w 1/2 SuperP) over 2mins

Increase to Speed 3 (mix 30 secs)

Increase to Speed 4 (mix 2min+1/2)

Increase to Speed 5 (mix 3min+1/2)

Increase to Speed 6 (mix 'til ball)

12 amps Turning Pt- Add SuperP

cont. mixing 'til motor evens out 6-7amps

Slow Speed 3-Add Fibers over 2mins

Slow Speed 1 (mix for 2 mins)

Flow Test (4 measurements) -20 Blows If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm

Before Blows

After Blows

0:00	0:00	72.5	
2:00	2:00	72.5	
4:15	4:22	73.5	
4:45	4:55	74.0	
7:15	7:15	75.0	
11:15	11:15	75.0	
--	16:10	86.5	12
--	18:15	86.5	7
26:30	18:15	89.0	
28:30	20:15	89.0	

		18L
Premix	(kg)	39.49
	(lb)	87.06
3000 NS	(kg)	0.54
	(lb)	1.19
Water	(kg)	2.32
	(lb)	5.11
Steel (2%)	(kg)	2.81
	(lb)	6.19

Lab Technicians

Jason, Miguel,
Sarah

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Table B.6
PSD mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

PSD Creep & Shrinkage Study

Date:	Time:	Room Temp:	Room RH:
18-Jul-11	7:01 PM	71.4°F	41%

Estimated
(18L)

Actual Time

Temp (°F)

Amps

Time start mixing

Add water(w 1/2 SuperP) over 2mins

Increase to Speed 3 (mix 30 secs)

Increase to Speed 4 (mix 2min+1/2)

Increase to Speed 5 (mix 3min+1/2)

Increase to Speed 6 (mix 'til ball)

12 amps Turning Pt- Add SuperP

cont. mixing 'til motor evens out 6-7amps

Slow Speed 3-Add Fibers over 2mins

Slow Speed 1 (mix for 2 mins)

Flow Test (4 measurements) -**20 Blows** If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm

Before Blows

After Blows

0:00	0:00	76.5	
2:00	2:00	76.5	
4:15	4:15	76.5	
4:45	4:45	76.5	
7:15	7:15	78.5	
11:15	11:30	78.5	
--	19:15	87.0	12
--	21:00	87.0	8
26:30	21:00	91.0	
28:30	23:00	92.0	

		18L
Premix	(kg)	39.49
	(lb)	87.06
3000 NS	(kg)	0.54
	(lb)	1.19
Water	(kg)	2.32
	(lb)	5.11
Steel (2%)	(kg)	2.81
	(lb)	6.19

Lab Technicians

Jason, Miguel,
Sarah, Eric

Table B.7
PDD mixing sheet

UHPC Mixing Lab Sheet

1000L = 1 m³ = 35.31467 ft³

PDD Creep & Shrinkage Study		Date: 12-Jul-11	Time: 6:02 PM	Room Temp: 72.0°F	Room RH: 42%
		Estimated (18L)	Actual Time	Temp (°F)	Amps
Time start mixing		0:00	0:00	73.5	
Add water(w 1/2 SuperP) over 2mins		2:00	3:20	74.0	
Increase to Speed 3 (mix 30 secs)		4:15	4:40	73.5	
Increase to Speed 4 (mix 2min+1/2)		4:45	5:10	74.0	
Increase to Speed 5 (mix 3min+1/2)		7:15	8:05	75.0	
Increase to Speed 6 (mix 'til ball)		11:15	12:05	75.5	
12 amps Turning Pt- Add SuperP		--	20:30	82.0	12
cont. mixing 'til motor evens out 6-7amps		--	22:45	87.5	7.5
Slow Speed 3-Add Fibers over 2mins		26:30	22:45	87.5	
Slow Speed 1 (mix for 2 mins)		28:30	24:45	90.0	
Flow Test (4 measurements) - 20 Blows If >200mm diameter, cast on vibrating table, Ideal flow is 230 – 235mm					
Before Blows		185	190	185	185
After Blows		220	225	230	230

		18L
Premix	(kg)	39.49
	(lb)	87.06
3000 NS	(kg)	0.54
	(lb)	1.19
Water	(kg)	2.32
	(lb)	5.11
Steel (2%)	(kg)	2.81
	(lb)	6.19

Lab Technicians
Jason, Miguel, Sarah, Eric

Appendix C - Compressive Strength Gain Data

Table C.1
PSC-1C compression data

UHPC Compression Data Sheet

Batch Date:
1/31/2011 5:00:00 PM Test Date: 2/1/2011
Batch: **PSC-1C**
Jason
Operator: *Flietstra*

Sample Number	Elapsed Time (hrs)	Actual Time	Cylinder Diameter (in)	Cylinder Area (sq. in)	Length (in)	Perp. Check	Plane Check	Max Load (lbs)	Strength (psi)	Initials
PSD COMP 1	12	5/18/2011	3	7.0686	6	x	x	70908	10031	JCF
PSD COMP 2	12	5/18/2011	3	7.0686	6	x	x	59185	8373	JCF
PSC-1C-14	14.0	7:00:00 AM	2.9775	6.9630	6.0120	X	X	106500	15295	JCF
PSC-1C-15	15.0	8:00:00 AM	3.0000	7.0686	6.0110	X	X	110299	15604	JCF
PSC-1C-16	16.0	9:00:00 AM	3.0010	7.0733	6.0193	X	X	116110	16415	JCF
PSC-1C-17	17.0	10:00:00 AM	3.0015	7.0757	6.0048	X	X	124933	17657	JCF
PSC-1C-17.5	17.5	10:30:00 AM	3.0053	7.0933	5.9693	X	X	119294	16818	JCF
PSC-1C-18	18.0	11:00:00 AM	3.0173	7.1501	5.9775	X	X	124666	17436	JCF
PSC-1C-18.5	18.5	11:30:00 AM	3.0053	7.0933	6.0365	X	X	131633	18557	JCF
PSC-1C-19	19.0	12:00:00 PM	3.0053	7.0933	6.0008	X	X	117719	16596	JCF
PSC-1C-19.5	19.5	12:30:00 PM	3.0525	7.3181	5.9850	X	X	137096	18734	JCF
PSC-1C-20	20.0	1:00:00 PM	3.0073	7.1028	6.0000	X	X	129772	18271	JCF
PSC-1C-21	21.0	2:00:00 PM	3.0108	7.1193	6.0080	X	X	133746	18786	JCF
PSC-1C-21	Did not test	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table C.2
ABC-1C compression data

UHPC Compression Data Sheet

Batch Date:
2/4/2011 5:00:00 PM Test Date: 2/6/2011 & 2/7/2011
Batch: **ABC-1C**
Jason
Operator: *Flietstra*

Sample Number	Elapsed Time (hrs)	Actual Time	Cylinder Diameter (in)	Cylinder Area (sq. in)	Length (in)	Perp. Check	Plane Check	Max Load (lbs)	Strength (psi)	Initials
ABC-1C-49	49.0	6:00:00 PM	3.0280	7.2011	6.0018	X	X	71343	9907	JCF
ABC-1C-62	62.0	8:00:00 AM	3.0005	7.0709	5.9848	X	X	87853	12425	JCF
ABC-1C-62.5	62.5	8:30:00 AM	3.0250	7.1869	6.0018	X	X	86690	12062	JCF
ABC-1C-63	63.0	9:00:00 AM	2.9598	6.8802	5.9930	X	X	86981	12642	JCF
ABC-1C-63.5	63.5	9:30:00 AM	3.0028	7.0815	6.0003	X	X	93751	13239	JCF
ABC-1C-64	64.0	10:00:00 AM	3.0125	7.1276	6.0048	X	X	92680	13003	JCF
ABC-1C-64.5	64.5	10:30:00 AM	2.9868	7.0063	5.9805	X	X	89709	12804	JCF
ABC-1C-65	65.0	11:00:00 AM	2.9985	7.0615	5.9658	X	X	96802	13708	JCF
ABC-1C-65.5	65.5	11:30:00 AM	3.0020	7.0780	6.0118	X	X	87813	12406	JCF
ABC-1C-66	66.0	12:00:00 PM	3.0095	7.1134	6.0035	X	X	94414	13273	JCF
ABC-1C-67	67.0	1:00:00 PM	2.9958	7.0486	6.0115	X	X	90590	12852	JCF
ABC-1C-70.5	70.5	4:30:00 PM	2.9968	7.0533	5.9950	X	X	101550	14398	JCF

Appendix D - Creep and Shrinkage Data

The following graphs and data present data of the creep and shrinkage results for each curing regime. The charts and data are limited to the timeframe of this research, and it is important to note that AMC, PSD, and PDD curing regimes remain under load. The graphed data includes an average value for strain (microstrain $10^{-6}\mu\epsilon$ in/in) of the three gage lengths on each specimen, plotted against time (days.) The graphs look at only the additional creep after the initial load has been applied to better define the inelastic creep effects of UHPC.

The data for initial and daily length change measurements is presented as the actual gage length reading by the Whittemore strain gage for each gage on the specimen.

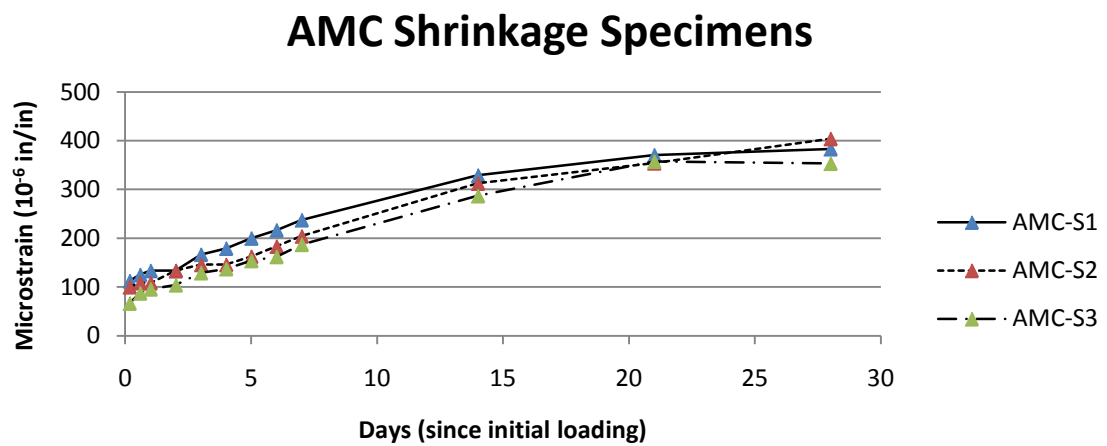
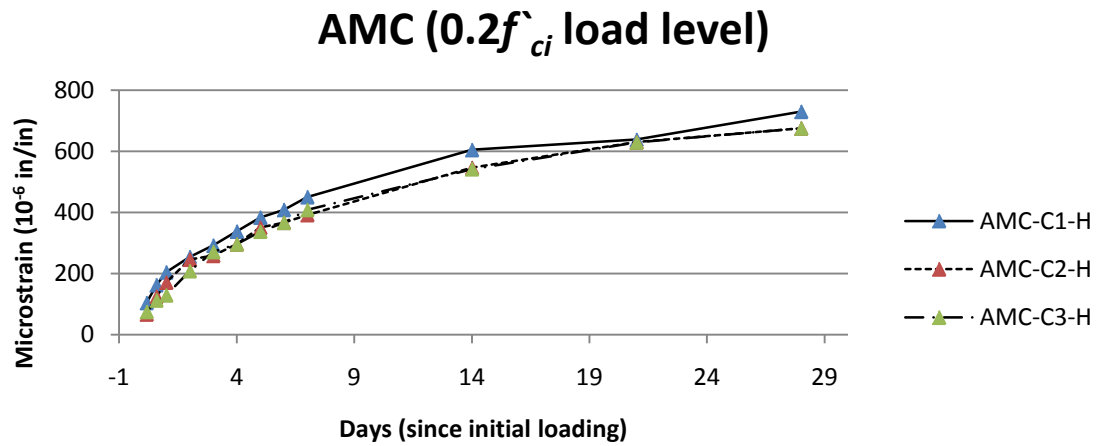
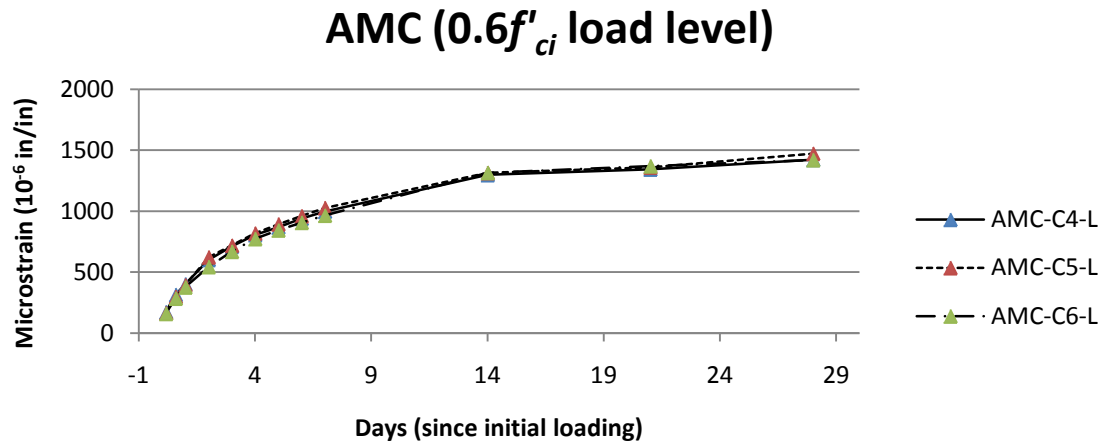


Figure D.1 AMC creep and shrinkage strains

Table D.1
AMC initial strain Data for creep specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: AMBIENT AIR CURE

Date: 7-1-11

Comp1 86630 lbs

Comp2 84290 lbs

UHPC Density (pcf): _____

Time: 2:00 PM

Comp3 84110 lbs

	Cylinder ID	Cylinder Weight (lb)	Diameter		Avg	Total Length (in)		Avg	Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured			Measured				Measured		Measured		Measured	Avg
Creep Specimens	AMC-C1-H	7.82	Φ ₁	3.0030	3.0000	L ₁	11.9705	11.9752	7.0686	G _{ib1}	0.258	G _{ia1}	0.262	500	617
			Φ ₂	2.9930		L ₂	11.9765			G _{ib2}	0.2515	G _{ia2}	0.2582	837	
			Φ ₃	3.0040		L ₃	11.9785			G _{ib3}	0.2542	G _{ia3}	0.2583	513	
	AMC-C2-H	7.73	Φ ₁	3.0010	3.0008	L ₁	11.9795	11.9768	7.0725	G _{ib1}	0.2442	G _{ia1}	0.249	599	554
			Φ ₂	2.9930		L ₂	11.9760			G _{ib2}	0.2525	G _{ia2}	0.258	687	
			Φ ₃	3.0085		L ₃	11.9750			G _{ib3}	0.2703	G _{ia3}	0.2733	376	
	AMC-C3-H	7.85	Φ ₁	3.0010	3.0027	L ₁	11.9835	11.9853	7.0811	G _{ib1}	0.2458	G _{ia1}	0.2485	337	566
			Φ ₂	3.0065		L ₂	11.9835			G _{ib2}	0.2489	G _{ia2}	0.2563	925	
			Φ ₃	3.0005		L ₃	11.9890			G _{ib3}	0.2497	G _{ia3}	0.2532	437	
	AMC-C4-L	7.73	Φ ₁	2.9925	2.9925	L ₁	11.9760	11.9747	7.0333	G _{ib1}	0.2514	G _{ia1}	0.2595	1012	1266
			Φ ₂	2.9925		L ₂	11.9720			G _{ib2}	0.2462	G _{ia2}	0.2585	1536	
			Φ ₃	2.9925		L ₃	11.9760			G _{ib3}	0.2599	G _{ia3}	0.2699	1251	
	AMC-C5-L	7.76	Φ ₁	2.9975	2.9975	L ₁	11.9665	11.9698	7.0568	G _{ib1}	0.2456	G _{ia1}	0.253	924	1250
			Φ ₂	2.9945		L ₂	11.9725			G _{ib2}	0.2508	G _{ia2}	0.2637	1612	
			Φ ₃	3.0005		L ₃	11.9705			G _{ib3}	0.2581	G _{ia3}	0.2678	1213	
	AMC-C6-L	7.73	Φ ₁	2.9975	2.9945	L ₁	11.9700	11.9692	7.0427	G _{ib1}	0.246	G _{ia1}	0.2567	1336	1292
			Φ ₂	2.9915		L ₂	11.9670			G _{ib2}	0.2667	G _{ia2}	0.2774	1340	
			Φ ₃	2.9945		L ₃	11.9705			G _{ib3}	0.257	G _{ia3}	0.2666	1201	

Table D.2
AMC initial data for shrinkage specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: AMBIENT AIR CURE

Date: 7-1-11

Comp1 86630 lbs

Comp2 84290 lbs

UHPC Density (pcf):

Time: 2:00 PM

Comp3 84110 lbs

	Cylinder ID	Cylinder Weight (lb)	Diameter		Avg	Total Length (in)		Avg	Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured			Measured								Measured	Avg
Shrinkage Specimens	AMC-S1	7.81	Φ ₁	3.0075	3.0038	L ₁	11.9905	11.9927	7.0867	G _{ib1}	0.2524	G _{ia1}			
			Φ ₂	3.0025		L ₂	11.9895			G _{ib2}	0.2441	G _{ia2}			
			Φ ₃	3.0015		L ₃	11.9980			G _{ib3}	0.2575	G _{ia3}			
	AMC-S2	7.78	Φ ₁	2.9985	2.9995	L ₁	11.9905	11.9855	7.0662	G _{ib1}	0.2548	G _{ia1}			
			Φ ₂	2.9970		L ₂	11.9835			G _{ib2}	0.255	G _{ia2}			
			Φ ₃	3.0030		L ₃	11.9825			G _{ib3}	0.2498	G _{ia3}			
	AMC-S3	7.81	Φ ₁	3.0020	2.9997	L ₁	11.9805	11.9807	7.0670	G _{ib1}	0.2458	G _{ia1}			
			Φ ₂	2.9980		L ₂	11.9800			G _{ib2}	0.2365	G _{ia2}			
			Φ ₃	2.9990		L ₃	11.9815			G _{ib3}	0.222	G _{ia3}			

Table D.3
AMC creep measurements

UHPC Creep and Shrinkage Raw Data Sheet

Curing Regime: AMBIENT AIR CURE

	Cylinder ID	Date: 7-1-11 Gage Length Reading, 4hr (in)		Date: 7-1-11 Gage Length Reading, 14hr (in)		Date: 7-2-11 Gage Length Reading, Day 1 (in)		Date: 7-3-11 Gage Length Reading, Day 2 (in)		Date: 7-4-11 Gage Length Reading, Day 3 (in)		Date: 7-5-11 Gage Length Reading, Day 4 (in)		Date: 7-6-11 Gage Length Reading, Day 5 (in)		Date: 7-7-11 Gage Length Reading, Day 6 (in)	
Creep Specimens	AMC-C1-H	G _{4h-1}	0.2630	G _{14h-1}	0.2633	G _{1d-1}	0.2635	G _{2d-1}	0.2637	G _{3d-1}	0.2642	G _{4d-1}	0.2646	G _{5d-1}	0.2650	G _{6d-1}	0.2652
		G _{4h-2}	0.2588	G _{14h-2}	0.2592	G _{1d-2}	0.2595	G _{2d-2}	0.2599	G _{3d-2}	0.2600	G _{4d-2}	0.2604	G _{5d-2}	0.2608	G _{6d-2}	0.2609
		G _{4h-3}	0.2592	G _{14h-3}	0.2599	G _{1d-3}	0.2604	G _{2d-3}	0.2610	G _{3d-3}	0.2613	G _{4d-3}	0.2616	G _{5d-3}	0.2619	G _{6d-3}	0.2622
	AMC-C2-H	G _{4h-1}	0.2498	G _{14h-1}	0.2501	G _{1d-1}	0.2504	G _{2d-1}	0.2511	G _{3d-1}	0.2512	G _{4d-1}	0.2508	G _{5d-1}	0.2518	G _{6d-1}	0.2520
		G _{4h-2}	0.2586	G _{14h-2}	0.2593	G _{1d-2}	0.2598	G _{2d-2}	0.2604	G _{3d-2}	0.2605	G _{4d-2}	0.2612	G _{5d-2}	0.2614	G _{6d-2}	0.2616
		G _{4h-3}	0.2735	G _{14h-3}	0.2739	G _{1d-3}	0.2742	G _{2d-3}	0.2747	G _{3d-3}	0.2748	G _{4d-3}	0.2754	G _{5d-3}	0.2755	G _{6d-3}	0.2755
	AMC-C3-H	G _{4h-1}	0.2491	G _{14h-1}	0.2493	G _{1d-1}	0.2495	G _{2d-1}	0.2500	G _{3d-1}	0.2504	G _{4d-1}	0.2502	G _{5d-1}	0.2506	G _{6d-1}	0.2508
		G _{4h-2}	0.2570	G _{14h-2}	0.2575	G _{1d-2}	0.2576	G _{2d-2}	0.2587	G _{3d-2}	0.2592	G _{4d-2}	0.2600	G _{5d-2}	0.2605	G _{6d-2}	0.2608
		G _{4h-3}	0.2537	G _{14h-3}	0.2539	G _{1d-3}	0.2540	G _{2d-3}	0.2543	G _{3d-3}	0.2549	G _{4d-3}	0.2549	G _{5d-3}	0.2550	G _{6d-3}	0.2552
	AMC-C4-L	G _{4h-1}	0.2611	G _{14h-1}	0.2624	G _{1d-1}	0.2632	G _{2d-1}	0.2653	G _{3d-1}	0.2660	G _{4d-1}	0.2670	G _{5d-1}	0.2678	G _{6d-1}	0.2686
		G _{4h-2}	0.2600	G _{14h-2}	0.2614	G _{1d-2}	0.2624	G _{2d-2}	0.2636	G _{3d-2}	0.2644	G _{4d-2}	0.2652	G _{5d-2}	0.2655	G _{6d-2}	0.2660
		G _{4h-3}	0.2709	G _{14h-3}	0.2716	G _{1d-3}	0.2719	G _{2d-3}	0.2734	G _{3d-3}	0.2745	G _{4d-3}	0.2750	G _{5d-3}	0.2754	G _{6d-3}	0.2758
	AMC-C5-L	G _{4h-1}	0.2541	G _{14h-1}	0.2555	G _{1d-1}	0.2564	G _{2d-1}	0.2587	G _{3d-1}	0.2595	G _{4d-1}	0.2608	G _{5d-1}	0.2617	G _{6d-1}	0.2621
		G _{4h-2}	0.2652	G _{14h-2}	0.2663	G _{1d-2}	0.2670	G _{2d-2}	0.2682	G _{3d-2}	0.2690	G _{4d-2}	0.2700	G _{5d-2}	0.2706	G _{6d-2}	0.2714
		G _{4h-3}	0.2691	G _{14h-3}	0.2698	G _{1d-3}	0.2705	G _{2d-3}	0.2725	G _{3d-3}	0.2732	G _{4d-3}	0.2733	G _{5d-3}	0.2736	G _{6d-3}	0.2740
	AMC-C6-L	G _{4h-1}	0.2578	G _{14h-1}	0.2586	G _{1d-1}	0.2594	G _{2d-1}	0.2608	G _{3d-1}	0.2614	G _{4d-1}	0.2620	G _{5d-1}	0.2627	G _{6d-1}	0.2632
		G _{4h-2}	0.2790	G _{14h-2}	0.2805	G _{1d-2}	0.2814	G _{2d-2}	0.2825	G _{3d-2}	0.2836	G _{4d-2}	0.2850	G _{5d-2}	0.2856	G _{6d-2}	0.2861
		G _{4h-3}	0.2677	G _{14h-3}	0.2684	G _{1d-3}	0.2689	G _{2d-3}	0.2704	G _{3d-3}	0.2717	G _{4d-3}	0.2722	G _{5d-3}	0.2726	G _{6d-3}	0.2731

Table D.3, continued

UHPC Creep and Shrinkage Data SheetCuring Regime: AMBIENT AIR CURE

UHPC Density (pcf): _____

	Cylinder ID	Date: 7-8-11 Gage Length Reading, Day 7 (in)		Date: 7-15-11 Gage Length Reading, Day 14 (in)		Date: 7-22-11 Gage Length Reading, Day 21 (in)		Date: 7-29-11 Gage Length Reading, 4 Week (in)	
Creep Specimens	AMC-C1-H	G _{7d-1}	0.2655	G _{2w-1}	0.2667	G _{3w-1}	0.2671	G _{2w-1}	0.2681
		G _{7d-2}	0.2613	G _{2w-2}	0.2625	G _{3w-2}	0.2627	G _{2w-2}	0.2634
		G _{7d-3}	0.2625	G _{2w-3}	0.2638	G _{3w-3}	0.264	G _{2w-3}	0.2645
	AMC-C2-H	G _{7d-1}	0.2519	G _{2w-1}	0.253	G _{3w-1}	0.254	G _{2w-1}	0.2545
		G _{7d-2}	0.262	G _{2w-2}	0.2634	G _{3w-2}	0.2639	G _{2w-2}	0.2643
		G _{7d-3}	0.2758	G _{2w-3}	0.277	G _{3w-3}	0.2775	G _{2w-3}	0.2777
	AMC-C3-H	G _{7d-1}	0.2511	G _{2w-1}	0.2519	G _{3w-1}	0.2527	G _{2w-1}	0.2530
		G _{7d-2}	0.2611	G _{2w-2}	0.2621	G _{3w-2}	0.2626	G _{2w-2}	0.2634
		G _{7d-3}	0.2556	G _{2w-3}	0.257	G _{3w-3}	0.2578	G _{2w-3}	0.2578
	AMC-C4-L	G _{7d-1}	0.2691	G _{2w-1}	0.2716	G _{3w-1}	0.2721	G _{2w-1}	0.2730
		G _{7d-2}	0.2666	G _{2w-2}	0.269	G _{3w-2}	0.269	G _{2w-2}	0.2696
		G _{7d-3}	0.2761	G _{2w-3}	0.2784	G _{3w-3}	0.279	G _{2w-3}	0.2794
	AMC-C5-L	G _{7d-1}	0.2626	G _{2w-1}	0.2652	G _{3w-1}	0.266	G _{2w-1}	0.2668
		G _{7d-2}	0.2719	G _{2w-2}	0.2737	G _{3w-2}	0.2737	G _{2w-2}	0.2750
		G _{7d-3}	0.2746	G _{2w-3}	0.2771	G _{3w-3}	0.2774	G _{2w-3}	0.2780
	AMC-C6-L	G _{7d-1}	0.2636	G _{2w-1}	0.2651	G _{3w-1}	0.2658	G _{2w-1}	0.2668
		G _{7d-2}	0.2868	G _{2w-2}	0.2911	G _{3w-2}	0.2909	G _{2w-2}	0.2906
		G _{7d-3}	0.2734	G _{2w-3}	0.276	G _{3w-3}	0.2768	G _{2w-3}	0.2773

Table D.4
AMC shrinkage measurements

UHPC Creep and Shrinkage Raw Data Sheet

Curing Regime: AMBIENT AIR CURE

	Cylinder ID	Date: 7-1-11 Gage Length Reading, 4hr (in)		Date: 7-1-11 Gage Length Reading, 14hr (in)		Date: 7-2-11 Gage Length Reading, Day 1 (in)		Date: 7-3-11 Gage Length Reading, Day 2 (in)		Date: 7-4-11 Gage Length Reading, Day 3 (in)		Date: 7-5-11 Gage Length Reading, Day 4 (in)		Date: 7-6-11 Gage Length Reading, Day 5 (in)		Date: 7-7-11 Gage Length Reading, Day 6 (in)	
Shrinkage Specimens	AMC-S1	G _{4h-1}	0.2532	G _{14h-1}	0.2533	G _{1d-1}	0.2534	G _{2d-1}	0.2534	G _{3d-1}	0.2537	G _{4d-1}	0.2539	G _{5d-1}	0.2541	G _{6d-1}	0.2542
		G _{4h-2}	0.2451	G _{14h-2}	0.2452	G _{1d-2}	0.2452	G _{2d-2}	0.2452	G _{3d-2}	0.2455	G _{4d-2}	0.2454	G _{5d-2}	0.2455	G _{6d-2}	0.2457
		G _{4h-3}	0.2584	G _{14h-3}	0.2585	G _{1d-3}	0.2586	G _{2d-3}	0.2586	G _{3d-3}	0.2588	G _{4d-3}	0.2590	G _{5d-3}	0.2592	G _{6d-3}	0.2593
	AMC-S2	G _{4h-1}	0.2557	G _{14h-1}	0.2557	G _{1d-1}	0.2557	G _{2d-1}	0.2560	G _{3d-1}	0.2561	G _{4d-1}	0.2559	G _{5d-1}	0.2561	G _{6d-1}	0.2562
		G _{4h-2}	0.2556	G _{14h-2}	0.2557	G _{1d-2}	0.2557	G _{2d-2}	0.2560	G _{3d-2}	0.2561	G _{4d-2}	0.2563	G _{5d-2}	0.2564	G _{6d-2}	0.2565
		G _{4h-3}	0.2507	G _{14h-3}	0.2508	G _{1d-3}	0.2508	G _{2d-3}	0.2508	G _{3d-3}	0.2509	G _{4d-3}	0.2509	G _{5d-3}	0.2510	G _{6d-3}	0.2513
	AMC-S3	G _{4h-1}	0.2464	G _{14h-1}	0.2465	G _{1d-1}	0.2466	G _{2d-1}	0.2466	G _{3d-1}	0.2467	G _{4d-1}	0.2465	G _{5d-1}	0.2467	G _{6d-1}	0.2468
		G _{4h-2}	0.2370	G _{14h-2}	0.2373	G _{1d-2}	0.2374	G _{2d-2}	0.2375	G _{3d-2}	0.2376	G _{4d-2}	0.2376	G _{5d-2}	0.2377	G _{6d-2}	0.2378
		G _{4h-3}	0.2225	G _{14h-3}	0.2226	G _{1d-3}	0.2226	G _{2d-3}	0.2227	G _{3d-3}	0.2231	G _{4d-3}	0.2235	G _{5d-3}	0.2236	G _{6d-3}	0.2236

Table D.4, continued

UHPC Creep and Shrinkage Raw Data SheetCuring Regime: AMBIENT AIR CURE

	Cylinder ID	Date: 7-8-11 Gage Length Reading, Day 7 (in)		Date: 7-15-11 Gage Length Reading, Day 14 (in)		Date: 7-22-11 Gage Length Reading, Day 21 (in)		Date: 7-29-11 Gage Length Reading, 4 Week (in)	
Shrinkage Specimens	AMC-S1	G _{7d-1}	0.2544	G _{2w-1}	0.2550	G _{3w-1}	0.2554	G _{2w-1}	0.2554
		G _{7d-2}	0.2459	G _{2w-2}	0.2467	G _{3w-2}	0.2470	G _{2w-2}	0.2474
		G _{7d-3}	0.2594	G _{2w-3}	0.2602	G _{3w-3}	0.2605	G _{2w-3}	0.2604
	AMC-S2	G _{7d-1}	0.2564	G _{2w-1}	0.2573	G _{3w-1}	0.2572	G _{2w-1}	0.2581
		G _{7d-2}	0.2566	G _{2w-2}	0.2574	G _{3w-2}	0.2580	G _{2w-2}	0.2582
		G _{7d-3}	0.2515	G _{2w-3}	0.2524	G _{3w-3}	0.2529	G _{2w-3}	0.2530
	AMC-S3	G _{7d-1}	0.2469	G _{2w-1}	0.2481	G _{3w-1}	0.2488	G _{2w-1}	0.2488
		G _{7d-2}	0.2380	G _{2w-2}	0.2389	G _{3w-2}	0.2393	G _{2w-2}	0.2392
		G _{7d-3}	0.2239	G _{2w-3}	0.2242	G _{3w-3}	0.2248	G _{2w-3}	0.2248

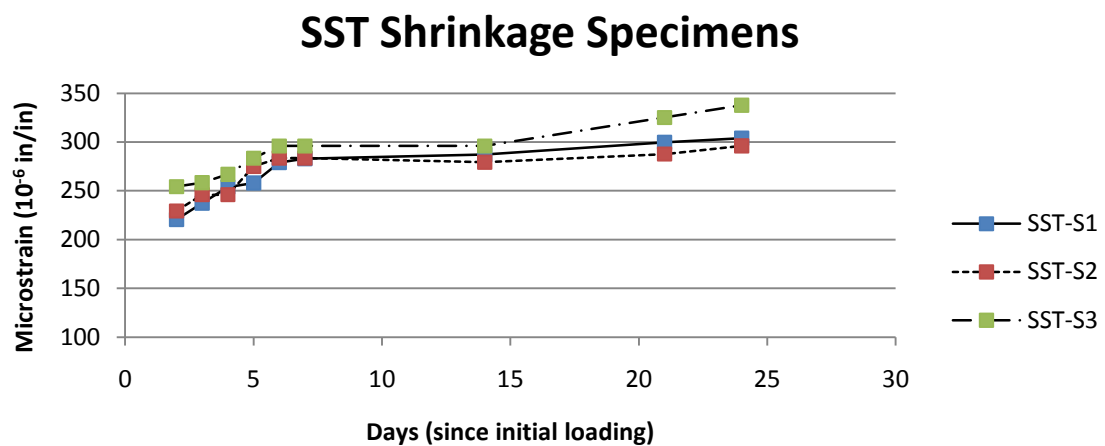
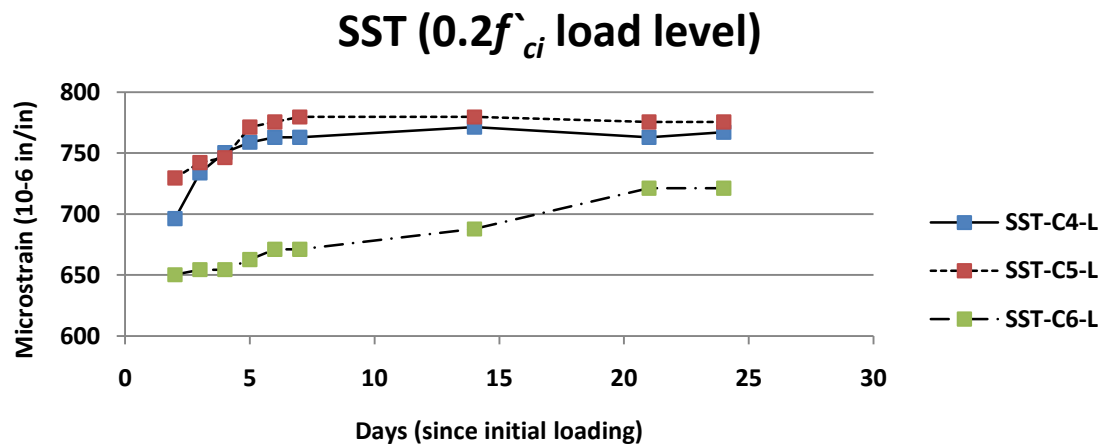
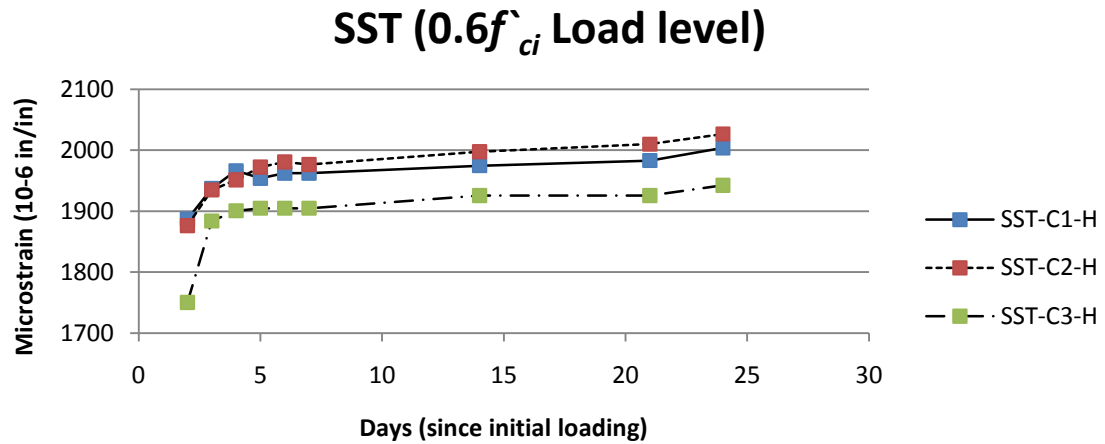


Figure D.2 SST creep and shrinkage strains

Table D.5
SST initial strain data for creep specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Standard Thermal Treatment Curing Regime (SST)

Date: 6-24-11

Comp1 96550 lbs

Comp2 95800 lbs

UHPC Density (pcf): _____

Time: 12:00 PM

Comp3 90200 lbs

	Cylinder ID	Cylinder Weight (lb)	Diameter		Avg	Total Length (in)		Avg	Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured			Measured								Measured	Avg
123 Creep Specimens	SST-C1-H	7.86	Φ ₁	2.9920	3.0028	L ₁	11.9910	11.9927	7.0819	G _{ib1}	0.2620	G _{ia1}	0.2730	1377	1426
			Φ ₂	3.0035		L ₂	11.9915			G _{ib2}	0.2407	G _{ia2}	0.2526	1485	
			Φ ₃	3.0130		L ₃	11.9955			G _{ib3}	0.2684	G _{ia3}	0.2797	1415	
	SST-C2-H	7.79	Φ ₁	3.0015	3.0002	L ₁	11.9805	11.9843	7.0694	G _{ib1}	0.2516	G _{ia1}	0.2625	1362	1481
			Φ ₂	3.0000		L ₂	11.9900			G _{ib2}	0.2526	G _{ia2}	0.2650	1550	
			Φ ₃	2.9990		L ₃	11.9825			G _{ib3}	0.2838	G _{ia3}	0.2960	1531	
	SST-C3-H	7.80	Φ ₁	3.0055	2.9993	L ₁	11.9890	11.9885	7.0654	G _{ib1}	0.2681	G _{ia1}	0.2804	1540	1576
			Φ ₂	2.9990		L ₂	11.9865			G _{ib2}	0.2705	G _{ia2}	0.2835	1629	
			Φ ₃	2.9935		L ₃	11.9900			G _{ib3}	0.2434	G _{ia3}	0.2559	1561	
	SST-C4-L	7.74	Φ ₁	2.9980	2.9978	L ₁	11.9715	11.9750	7.0584	G _{ib1}	0.2675	G _{ia1}	0.2713	476	504
			Φ ₂	2.9930		L ₂	11.9765			G _{ib2}	0.2503	G _{ia2}	0.2546	537	
			Φ ₃	3.0025		L ₃	11.9770			G _{ib3}	0.2442	G _{ia3}	0.2482	499	
	SST-C5-L	7.78	Φ ₁	2.9955	2.9973	L ₁	11.9795	11.9808	7.0560	G _{ib1}	0.2537	G _{ia1}	0.2583	575	513
			Φ ₂	2.9940		L ₂	11.9795			G _{ib2}	0.2553	G _{ia2}	0.2587	425	
			Φ ₃	3.0025		L ₃	11.9835			G _{ib3}	0.2517	G _{ia3}	0.2560	537	
	SST-C6-L	7.78	Φ ₁	2.9955	2.9935	L ₁	11.9785	11.9797	7.0380	G _{ib1}	0.2707	G _{ia1}	0.2752	564	471
			Φ ₂	2.9925		L ₂	11.9795			G _{ib2}	0.2436	G _{ia2}	0.2475	487	
			Φ ₃	2.9925		L ₃	11.9810			G _{ib3}	0.2431	G _{ia3}	0.2460	362	

Table D.6
SST initial data for shrinkage specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Standard Steam Curing Regime (SST)

Date: 6-24-11

UHPC Density (pcf): _____

Time: 12:00 PM

Comp 1 96550 lbs
Comp 2 95800 lbs
Comp 3 90200 lbs

	Cylinder ID	Cylinder Weight (lb)	Diameter		Total Length (in)			Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured	Avg	Measured	Avg							Measured	Avg
Shrinkage Specimens	SST-S1	7.74	Φ ₁	2.9970	3.0033	L ₁	11.9720	11.9757	7.0843	G _{ib1}	0.2454	G _{ia1}		
			Φ ₂	3.0055		L ₂	11.9795			G _{ib2}	0.2512	G _{ia2}		
			Φ ₃	3.0075		L ₃	11.9755			G _{ib3}	0.2389	G _{ia3}		
	SST-S2	7.72	Φ ₁	3.0020	3.0002	L ₁	11.9850	11.9845	7.0694	G _{ib1}	0.2509	G _{ia1}		
			Φ ₂	2.9960		L ₂	11.9815			G _{ib2}	0.2748	G _{ia2}		
			Φ ₃	3.0025		L ₃	11.9870			G _{ib3}	0.2502	G _{ia3}		
	SST-S3	7.78	Φ ₁	3.0080	3.0070	L ₁	11.9950	12.0047	7.1016	G _{ib1}	0.2556	G _{ia1}		
			Φ ₂	3.0045		L ₂	12.0015			G _{ib2}	0.2642	G _{ia2}		
			Φ ₃	3.0085		L ₃	12.0175			G _{ib3}	0.2516	G _{ia3}		

Table D.7
SST creep measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Standard Steam Cure

UHPC Density (pcf): _____

	Cylinder ID	Date: 6-26-11 Gage Length Reading, Day 2 (in)		Date: 6-27-11 Gage Length Reading, Day 3 (in)		Date: 6-28-11 Gage Length Reading, Day 4 (in)		Date: 6-29-11 Gage Length Reading, Day 5 (in)		Date: 6-30-11 Gage Length Reading, Day 6 (in)		Date: 7-1-11 Gage Length Reading, Day 7 (in)		Date: 7-8-11 Gage Length Reading, Day 14 (in)		Date: 7-15-11 Gage Length Reading, Day 21 (in)		Date: 7-18-11 Gage Length Reading, 24day (in)	
Creep Specimens	SST-C1-H	G _{2d-1}	0.2863	G _{3d-1}	0.2869	G _{4d-1}	0.2872	G _{5d-1}	0.2875	G _{6d-1}	0.2875	G _{7d-1}	0.2875	G _{2w-1}	0.2876	G _{3w-1}	0.2879	G _{4h-1}	0.288
		G _{2d-2}	0.2683	G _{3d-2}	0.2686	G _{4d-2}	0.2687	G _{5d-2}	0.2684	G _{6d-2}	0.2686	G _{7d-2}	0.2686	G _{2w-2}	0.2686	G _{3w-2}	0.2686	G _{4h-2}	0.269
		G _{2d-3}	0.2959	G _{3d-3}	0.2962	G _{4d-3}	0.2965	G _{5d-3}	0.2962	G _{6d-3}	0.2962	G _{7d-3}	0.2962	G _{2w-3}	0.2964	G _{3w-3}	0.2963	G _{4h-3}	0.2963
	SST-C2-H	G _{2d-1}	0.2757	G _{3d-1}	0.2760	G _{4d-1}	0.2761	G _{5d-1}	0.2763	G _{6d-1}	0.2763	G _{7d-1}	0.2763	G _{2w-1}	0.2764	G _{3w-1}	0.2765	G _{4h-1}	0.2766
		G _{2d-2}	0.2805	G _{3d-2}	0.2806	G _{4d-2}	0.2808	G _{5d-2}	0.2810	G _{6d-2}	0.2811	G _{7d-2}	0.2810	G _{2w-2}	0.2812	G _{3w-2}	0.2813	G _{4h-2}	0.2814
		G _{2d-3}	0.3122	G _{3d-3}	0.3132	G _{4d-3}	0.3133	G _{5d-3}	0.3134	G _{6d-3}	0.3135	G _{7d-3}	0.3135	G _{2w-3}	0.3137	G _{3w-3}	0.3138	G _{4h-3}	0.314
	SST-C3-H	G _{2d-1}	0.295	G _{3d-1}	0.2968	G _{4d-1}	0.2970	G _{5d-1}	0.2970	G _{6d-1}	0.2970	G _{7d-1}	0.2970	G _{2w-1}	0.2972	G _{3w-1}	0.2972	G _{4h-1}	0.2972
		G _{2d-2}	0.2962	G _{3d-2}	0.2970	G _{4d-2}	0.2972	G _{5d-2}	0.2973	G _{6d-2}	0.2973	G _{7d-2}	0.2973	G _{2w-2}	0.2975	G _{3w-2}	0.2975	G _{4h-2}	0.2976
		G _{2d-3}	0.2705	G _{3d-3}	0.2711	G _{4d-3}	0.2711	G _{5d-3}	0.2711	G _{6d-3}	0.2711	G _{7d-3}	0.2711	G _{2w-3}	0.2712	G _{3w-3}	0.2712	G _{4h-3}	0.2715
	SST-C4-L	G _{2d-1}	0.277	G _{3d-1}	0.2776	G _{4d-1}	0.2776	G _{5d-1}	0.2776	G _{6d-1}	0.2777	G _{7d-1}	0.2777	G _{2w-1}	0.2777	G _{3w-1}	0.2776	G _{4h-1}	0.2777
		G _{2d-2}	0.2595	G _{3d-2}	0.2596	G _{4d-2}	0.2598	G _{5d-2}	0.2600	G _{6d-2}	0.2600	G _{7d-2}	0.2600	G _{2w-2}	0.2600	G _{3w-2}	0.2600	G _{4h-2}	0.2601
		G _{2d-3}	0.2543	G _{3d-3}	0.2545	G _{4d-3}	0.2547	G _{5d-3}	0.2547	G _{6d-3}	0.2547	G _{7d-3}	0.2547	G _{2w-3}	0.2549	G _{3w-3}	0.2548	G _{4h-3}	0.2547
	SST-C5-L	G _{2d-1}	0.264	G _{3d-1}	0.2644	G _{4d-1}	0.2644	G _{5d-1}	0.2645	G _{6d-1}	0.2645	G _{7d-1}	0.2646	G _{2w-1}	0.2647	G _{3w-1}	0.2648	G _{4h-1}	0.2648
		G _{2d-2}	0.2655	G _{3d-2}	0.2649	G _{4d-2}	0.2650	G _{5d-2}	0.2650	G _{6d-2}	0.2650	G _{7d-2}	0.2650	G _{2w-2}	0.2652	G _{3w-2}	0.2650	G _{4h-2}	0.2651
		G _{2d-3}	0.261	G _{3d-3}	0.2615	G _{4d-3}	0.2615	G _{5d-3}	0.2620	G _{6d-3}	0.2621	G _{7d-3}	0.2621	G _{2w-3}	0.2618	G _{3w-3}	0.2618	G _{4h-3}	0.2617
	SST-C6-L	G _{2d-1}	0.28	G _{3d-1}	0.2800	G _{4d-1}	0.2800	G _{5d-1}	0.2802	G _{6d-1}	0.2803	G _{7d-1}	0.2803	G _{2w-1}	0.2805	G _{3w-1}	0.2808	G _{4h-1}	0.2808
		G _{2d-2}	0.253	G _{3d-2}	0.2530	G _{4d-2}	0.2530	G _{5d-2}	0.2530	G _{6d-2}	0.2531	G _{7d-2}	0.2531	G _{2w-2}	0.2533	G _{3w-2}	0.2538	G _{4h-2}	0.2538
		G _{2d-3}	0.2513	G _{3d-3}	0.2514	G _{4d-3}	0.2514	G _{5d-3}	0.2514	G _{6d-3}	0.2514	G _{7d-3}	0.2514	G _{2w-3}	0.2514	G _{3w-3}	0.2514	G _{4h-3}	0.2514

Table D.8
SST shrinkage measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Standard Steam Cure (SST)

	Cylinder ID	Date: 6-26-11 Gage Length Reading, Day 2 (in)		Date: 6-27-11 Gage Length Reading, Day 3 (in)		Date: 6-28-11 Gage Length Reading, Day 4 (in)		Date: 6-29-11 Gage Length Reading, Day 5 (in)		Date: 6-30-11 Gage Length Reading, Day 6 (in)		Date: 7-1-11 Gage Length Reading, Day 7 (in)		Date: 7-8-11 Gage Length Reading, Day 14 (in)		Date: 7-15-11 Gage Length Reading, Day 21 (in)		Date: 7-18-11 Gage Length Reading, 24day (in)	
Shrinkage Specimens	SST-S1	G _{2d-1}	0.2476	G _{3d-1}	0.2477	G _{4d-1}	0.2478	G _{5d-1}	0.2476	G _{6d-1}	0.2478	G _{7d-1}	0.2479	G _{2w-1}	0.2479	G _{3w-1}	0.2479	G _{4h-1}	0.2479
		G _{2d-2}	0.2527	G _{3d-2}	0.2528	G _{4d-2}	0.2529	G _{5d-2}	0.2531	G _{6d-2}	0.2533	G _{7d-2}	0.2533	G _{2w-2}	0.2533	G _{3w-2}	0.2535	G _{4h-2}	0.2536
		G _{2d-3}	0.2405	G _{3d-3}	0.2407	G _{4d-3}	0.2409	G _{5d-3}	0.2410	G _{6d-3}	0.2411	G _{7d-3}	0.2411	G _{2w-3}	0.2412	G _{3w-3}	0.2413	G _{4h-3}	0.2413
	SST-S2	G _{2d-1}	0.2523	G _{3d-1}	0.2524	G _{4d-1}	0.2524	G _{5d-1}	0.2528	G _{6d-1}	0.2528	G _{7d-1}	0.2528	G _{2w-1}	0.2528	G _{3w-1}	0.2528	G _{4h-1}	0.2528
		G _{2d-2}	0.2769	G _{3d-2}	0.2770	G _{4d-2}	0.2770	G _{5d-2}	0.2770	G _{6d-2}	0.2771	G _{7d-2}	0.2771	G _{2w-2}	0.2770	G _{3w-2}	0.2770	G _{4h-2}	0.277
		G _{2d-3}	0.2522	G _{3d-3}	0.2524	G _{4d-3}	0.2524	G _{5d-3}	0.2527	G _{6d-3}	0.2528	G _{7d-3}	0.2528	G _{2w-3}	0.2528	G _{3w-3}	0.2530	G _{4h-3}	0.2532
	SST-S3	G _{2d-1}	0.2577	G _{3d-1}	0.2577	G _{4d-1}	0.2578	G _{5d-1}	0.2580	G _{6d-1}	0.2582	G _{7d-1}	0.2582	G _{2w-1}	0.2582	G _{3w-1}	0.2584	G _{4h-1}	0.2584
		G _{2d-2}	0.2661	G _{3d-2}	0.2661	G _{4d-2}	0.2662	G _{5d-2}	0.2663	G _{6d-2}	0.2663	G _{7d-2}	0.2663	G _{2w-2}	0.2663	G _{3w-2}	0.2666	G _{4h-2}	0.2666
		G _{2d-3}	0.2537	G _{3d-3}	0.2538	G _{4d-3}	0.2538	G _{5d-3}	0.2539	G _{6d-3}	0.2540	G _{7d-3}	0.2540	G _{2w-3}	0.2540	G _{3w-3}	0.2542	G _{4h-3}	0.2545

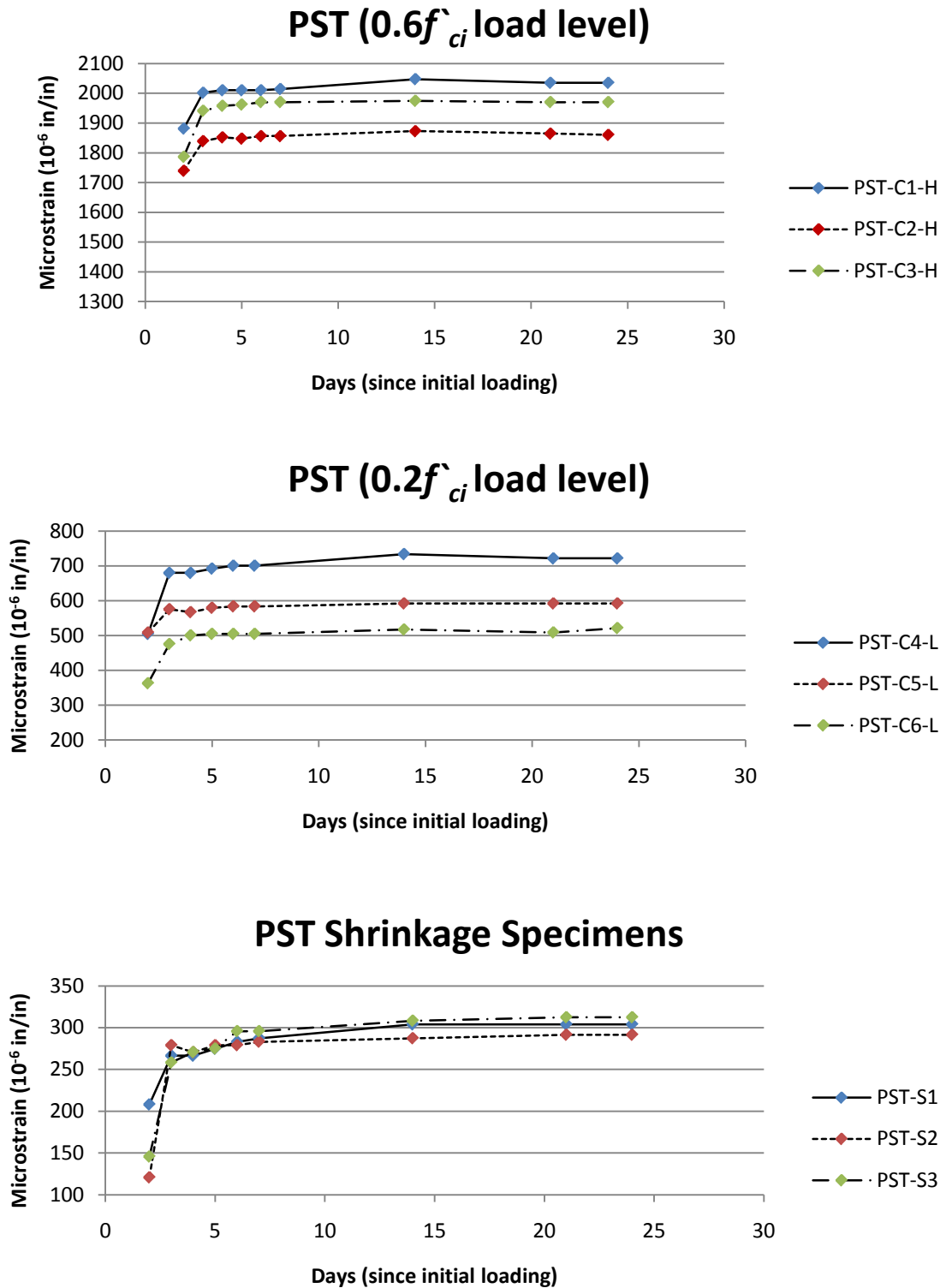


Figure D.3 PST creep and shrinkage strains

Table D.9
PST initial strain data for creep specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Presteam Curing Regime (PST)

UHPC Density (pcf): _____

Date: 6-17-11

Time: 1:00 PM

Comp1 100940 lbs

Comp2 94620 lbs

Comp3 96990 lbs

	Cylinder ID	Cylinder Weight (lb)	Diameter			Total Length (in)			Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured	Avg		Measured	Avg							Measured	Avg
Creep Specimens	PST-C1-H	7.78	Φ ₁	3.0005	3.0053	L ₁	11.9940	11.9890	7.09373	G _{ib1}	0.2575	G _{ia1}	0.2698	1538	1441
			Φ ₂	3.0065		L ₂	11.9840			G _{ib2}	0.2459	G _{ia2}	0.2583	1549	
			Φ ₃	3.0090		L ₃	11.9890			G _{ib3}	0.2453	G _{ia3}	0.2552	1236	
	PST-C2-H	7.83	Φ ₁	3.0010	3.0042	L ₁	11.9830	11.9862	7.08823	G _{ib1}	0.2487	G _{ia1}	0.2597	1374	1553
			Φ ₂	3.0095		L ₂	11.9955			G _{ib2}	0.2420	G _{ia2}	0.2570	1872	
			Φ ₃	3.0020		L ₃	11.9800			G _{ib3}	0.2594	G _{ia3}	0.2707	1414	
	PST-C3-H	7.79	Φ ₁	3.0100	3.0003	L ₁	12.0040	11.9993	7.07015	G _{ib1}	0.2516	G _{ia1}	0.2607	1137	1513
			Φ ₂	2.9930		L ₂	11.9960			G _{ib2}	0.2513	G _{ia2}	0.2663	1875	
			Φ ₃	2.9980		L ₃	11.9980			G _{ib3}	0.2618	G _{ia3}	0.2740	1527	
	PST-C4-L	7.75	Φ ₁	2.9995	3.0030	L ₁	12.0060	12.0023	7.08272	G _{ib1}	0.2544	G _{ia1}	0.2576	400	562
			Φ ₂	3.0040		L ₂	12.0015			G _{ib2}	0.2613	G _{ia2}	0.2639	325	
			Φ ₃	3.0055		L ₃	11.9995			G _{ib3}	0.2482	G _{ia3}	0.2559	962	
	PST-C5-L	7.81	Φ ₁	3.0005	3.0000	L ₁	11.9900	11.9930	7.06858	G _{ib1}	0.2571	G _{ia1}	0.2617	575	571
			Φ ₂	2.9955		L ₂	11.9925			G _{ib2}	0.2380	G _{ia2}	0.2419	487	
			Φ ₃	3.0040		L ₃	11.9965			G _{ib3}	0.2542	G _{ia3}	0.2594	650	
	PST-C6-L	7.8	Φ ₁	2.9975	2.9995	L ₁	11.9830	11.9842	7.06622	G _{ib1}	0.2458	G _{ia1}	0.2506	599	587
			Φ ₂	2.9955		L ₂	11.9870			G _{ib2}	0.2500	G _{ia2}	0.2548	600	
			Φ ₃	3.0055		L ₃	11.9825			G _{ib3}	0.2518	G _{ia3}	0.2563	562	

Table D.10
PST initial data for shrinkage specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Presteam Curing Regime (PST)

Date: 6-17-11

Comp1 100940 lbs

Comp2 94620 lbs

UHPC Density (pcf): _____

Time: 1:00 PM

Comp3 96990 lbs

	Cylinder ID	Cylinder Weight (lb)	Diameter			Total Length (in)			Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured	Avg		Measured	Avg							Measured	Avg
Shrinkage Specimens	PST-S1	7.82	Φ ₁	2.9985	3.0032	L ₁	11.9785	11.9815	7.08351	G _{ib1}	0.2488	G _{ia1}			
			Φ ₂	3.0020		L ₂	11.9870			G _{ib2}	0.2520	G _{ia2}			
			Φ ₃	3.0090		L ₃	11.9790			G _{ib3}	0.2353	G _{ia3}			
	PST-S2	7.73	Φ ₁	3.0050	3.0015	L ₁	11.9860	11.9882	7.07565	G _{ib1}	0.2505	G _{ia1}			
			Φ ₂	2.9980		L ₂	11.9885			G _{ib2}	0.2591	G _{ia2}			
			Φ ₃	3.0015		L ₃	11.9900			G _{ib3}	0.2230	G _{ia3}			
	PST-S3	7.76	Φ ₁	2.9970	3.0033	L ₁	11.9855	11.9868	7.08429	G _{ib1}	0.2644	G _{ia1}			
			Φ ₂	3.0095		L ₂	11.9910			G _{ib2}	0.2594	G _{ia2}			
			Φ ₃	3.0035		L ₃	11.9840			G _{ib3}	0.2404	G _{ia3}			

Table D.11
PST creep measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam standard cure PST

	Cylinder ID	Date: 6-19-11 Gage Length Reading, Day 2 (in)		Date: 6-20-11 Gage Length Reading, Day 3 (in)		Date: 6-21-11 Gage Length Reading, Day 4 (in)		Date: 6-22-11 Gage Length Reading, Day 5 (in)		Date: 6-23-11 Gage Length Reading, Day 6 (in)		Date: 6-24-11 Gage Length Reading, Day 7 (in)		Date: 7-1-11 Gage Length Reading, Day 14 (in)		Date: 7-8-11 Gage Length Reading, Day 21 (in)		Date: 7-11-11 Gage Length Reading, 24day (in)	
		G _{2d-1}		G _{3d-1}		G _{4d-1}		G _{5d-1}		G _{6d-1}		G _{7d-1}		G _{2w-1}		G _{3w-1}		G _{4h-1}	
Creep Specimens	PST-C1-H	G _{2d-1}	0.2852	G _{3d-1}	0.2855	G _{4d-1}	0.2857	G _{5d-1}	0.2858	G _{6d-1}	0.2858	G _{7d-1}	0.2858	G _{2w-1}	0.2859	G _{3w-1}	0.2859	G _{4h-1}	0.2859
		G _{2d-2}	0.2713	G _{3d-2}	0.2725	G _{4d-2}	0.2725	G _{5d-2}	0.2723	G _{6d-2}	0.2723	G _{7d-2}	0.2724	G _{2w-2}	0.273	G _{3w-2}	0.2727	G _{4h-2}	0.2727
		G _{2d-3}	0.2719	G _{3d-3}	0.2733	G _{4d-3}	0.2733	G _{5d-3}	0.2734	G _{6d-3}	0.2734	G _{7d-3}	0.2734	G _{2w-3}	0.2735	G _{3w-3}	0.2735	G _{4h-3}	0.2735
	PST-C2-H	G _{2d-1}	0.2733	G _{3d-1}	0.2744	G _{4d-1}	0.2744	G _{5d-1}	0.2744	G _{6d-1}	0.2745	G _{7d-1}	0.2745	G _{2w-1}	0.2746	G _{3w-1}	0.2746	G _{4h-1}	0.2745
		G _{2d-2}	0.2718	G _{3d-2}	0.2729	G _{4d-2}	0.2729	G _{5d-2}	0.2729	G _{6d-2}	0.2729	G _{7d-2}	0.2729	G _{2w-2}	0.273	G _{3w-2}	0.2729	G _{4h-2}	0.2729
		G _{2d-3}	0.2840	G _{3d-3}	0.2842	G _{4d-3}	0.2845	G _{5d-3}	0.2844	G _{6d-3}	0.2845	G _{7d-3}	0.2845	G _{2w-3}	0.2847	G _{3w-3}	0.2846	G _{4h-3}	0.2846
	PST-C3-H	G _{2d-1}	0.2723	G _{3d-1}	0.2735	G _{4d-1}	0.2734	G _{5d-1}	0.2736	G _{6d-1}	0.2738	G _{7d-1}	0.2738	G _{2w-1}	0.2738	G _{3w-1}	0.2738	G _{4h-1}	0.2738
		G _{2d-2}	0.2824	G _{3d-2}	0.2831	G _{4d-2}	0.2831	G _{5d-2}	0.2830	G _{6d-2}	0.2830	G _{7d-2}	0.2830	G _{2w-2}	0.2832	G _{3w-2}	0.2831	G _{4h-2}	0.2831
		G _{2d-3}	0.2891	G _{3d-3}	0.2909	G _{4d-3}	0.2914	G _{5d-3}	0.2914	G _{6d-3}	0.2914	G _{7d-3}	0.2914	G _{2w-3}	0.2913	G _{3w-3}	0.2913	G _{4h-3}	0.2913
	PST-C4-L	G _{2d-1}	0.2612	G _{3d-1}	0.2628	G _{4d-1}	0.2627	G _{5d-1}	0.2627	G _{6d-1}	0.2629	G _{7d-1}	0.2629	G _{2w-1}	0.2631	G _{3w-1}	0.2629	G _{4h-1}	0.2629
		G _{2d-2}	0.2684	G _{3d-2}	0.2698	G _{4d-2}	0.2698	G _{5d-2}	0.2698	G _{6d-2}	0.2698	G _{7d-2}	0.2698	G _{2w-2}	0.2701	G _{3w-2}	0.27	G _{4h-2}	0.27
		G _{2d-3}	0.2599	G _{3d-3}	0.2611	G _{4d-3}	0.2612	G _{5d-3}	0.2615	G _{6d-3}	0.2615	G _{7d-3}	0.2615	G _{2w-3}	0.2618	G _{3w-3}	0.2618	G _{4h-3}	0.2618
	PST-C5-L	G _{2d-1}	0.2660	G _{3d-1}	0.2663	G _{4d-1}	0.2661	G _{5d-1}	0.2662	G _{6d-1}	0.2662	G _{7d-1}	0.2662	G _{2w-1}	0.2662	G _{3w-1}	0.2662	G _{4h-1}	0.2662
		G _{2d-2}	0.2452	G _{3d-2}	0.2456	G _{4d-2}	0.2456	G _{5d-2}	0.2458	G _{6d-2}	0.2459	G _{7d-2}	0.2459	G _{2w-2}	0.2461	G _{3w-2}	0.2461	G _{4h-2}	0.2461
		G _{2d-3}	0.2640	G _{3d-3}	0.2649	G _{4d-3}	0.2649	G _{5d-3}	0.2649	G _{6d-3}	0.2649	G _{7d-3}	0.2649	G _{2w-3}	0.2649	G _{3w-3}	0.2649	G _{4h-3}	0.2649
	PST-C6-L	G _{2d-1}	0.2536	G _{3d-1}	0.2548	G _{4d-1}	0.2549	G _{5d-1}	0.2549	G _{6d-1}	0.2549	G _{7d-1}	0.2549	G _{2w-1}	0.2551	G _{3w-1}	0.255	G _{4h-1}	0.2551
		G _{2d-2}	0.2571	G _{3d-2}	0.2578	G _{4d-2}	0.2581	G _{5d-2}	0.2582	G _{6d-2}	0.2582	G _{7d-2}	0.2582	G _{2w-2}	0.2583	G _{3w-2}	0.2582	G _{4h-2}	0.2583
		G _{2d-3}	0.2597	G _{3d-3}	0.2605	G _{4d-3}	0.2607	G _{5d-3}	0.2607	G _{6d-3}	0.2607	G _{7d-3}	0.2607	G _{2w-3}	0.2607	G _{3w-3}	0.2607	G _{4h-3}	0.2608

Table D.12
PST shrinkage measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam standard cure (PST)

	Cylinder ID	Date: 6-19-11 Gage Length Reading, Day 2 (in)		Date: 6-20-11 Gage Length Reading, Day 3 (in)		Date: 6-21-11 Gage Length Reading, Day 4 (in)		Date: 6-22-11 Gage Length Reading, Day 5 (in)		Date: 6-23-11 Gage Length Reading, Day 6 (in)		Date: 6-24-11 Gage Length Reading, Day 7 (in)		Date: 7-1-11 Gage Length Reading, Day 14 (in)		Date: 7-8-11 Gage Length Reading, Day 21 (in)		Date: 7-11-11 Gage Length Reading, 24day (in)	
		G _{2d-1}		G _{3d-1}		G _{4d-1}		G _{5d-1}		G _{6d-1}		G _{7d-1}		G _{2w-1}		G _{3w-1}		G ₂₄₋₁	
Shrinkage Specimens	PST-S1	G _{2d-1}	0.2501	G _{3d-1}	0.2503	G _{4d-1}	0.2503	G _{5d-1}	0.2503	G _{6d-1}	0.2504	G _{7d-1}	0.2504	G _{2w-1}	0.2506	G _{3w-1}	0.2506	G ₂₄₋₁	0.2506
		G _{2d-2}	0.2546	G _{3d-2}	0.2552	G _{4d-2}	0.2553	G _{5d-2}	0.2553	G _{6d-2}	0.2553	G _{7d-2}	0.2553	G _{2w-2}	0.2554	G _{3w-2}	0.2554	G ₂₄₋₂	0.2554
		G _{2d-3}	0.2364	G _{3d-3}	0.2370	G _{4d-3}	0.2369	G _{5d-3}	0.2371	G _{6d-3}	0.2372	G _{7d-3}	0.2373	G _{2w-3}	0.2374	G _{3w-3}	0.2374	G ₂₄₋₃	0.2374
	PST-S2	G _{2d-1}	0.2511	G _{3d-1}	0.2527	G _{4d-1}	0.2525	G _{5d-1}	0.2526	G _{6d-1}	0.2526	G _{7d-1}	0.2526	G _{2w-1}	0.2526	G _{3w-1}	0.2526	G ₂₄₋₁	0.2526
		G _{2d-2}	0.2609	G _{3d-2}	0.2619	G _{4d-2}	0.2620	G _{5d-2}	0.2620	G _{6d-2}	0.2620	G _{7d-2}	0.2620	G _{2w-2}	0.262	G _{3w-2}	0.2621	G ₂₄₋₂	0.2621
		G _{2d-3}	0.2235	G _{3d-3}	0.2247	G _{4d-3}	0.2246	G _{5d-3}	0.2247	G _{6d-3}	0.2247	G _{7d-3}	0.2248	G _{2w-3}	0.2249	G _{3w-3}	0.2249	G ₂₄₋₃	0.2249
	PST-S3	G _{2d-1}	0.2646	G _{3d-1}	0.2660	G _{4d-1}	0.2660	G _{5d-1}	0.2660	G _{6d-1}	0.2660	G _{7d-1}	0.2660	G _{2w-1}	0.266	G _{3w-1}	0.266	G ₂₄₋₁	0.266
		G _{2d-2}	0.2613	G _{3d-2}	0.2617	G _{4d-2}	0.2619	G _{5d-2}	0.2622	G _{6d-2}	0.2625	G _{7d-2}	0.2625	G _{2w-2}	0.2627	G _{3w-2}	0.2627	G ₂₄₋₂	0.2627
		G _{2d-3}	0.2418	G _{3d-3}	0.2427	G _{4d-3}	0.2428	G _{5d-3}	0.2426	G _{6d-3}	0.2428	G _{7d-3}	0.2428	G _{2w-3}	0.2429	G _{3w-3}	0.243	G ₂₄₋₃	0.243

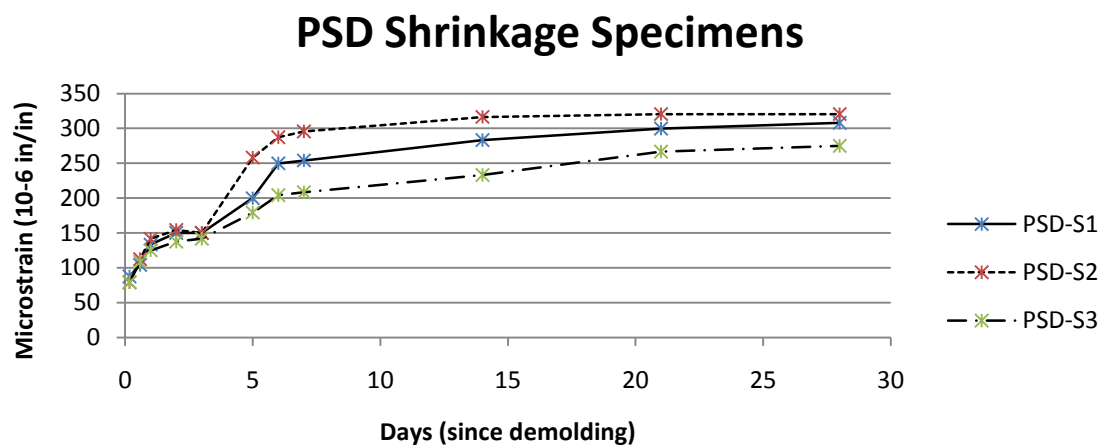
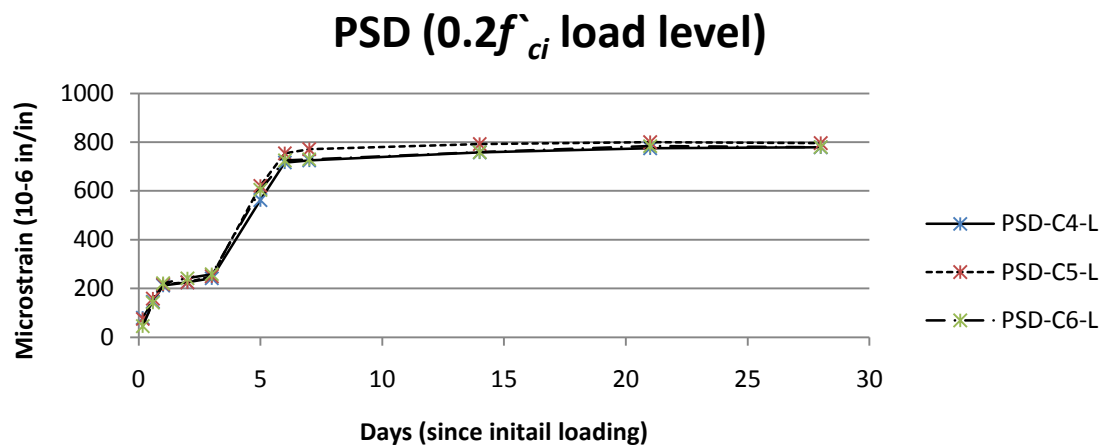
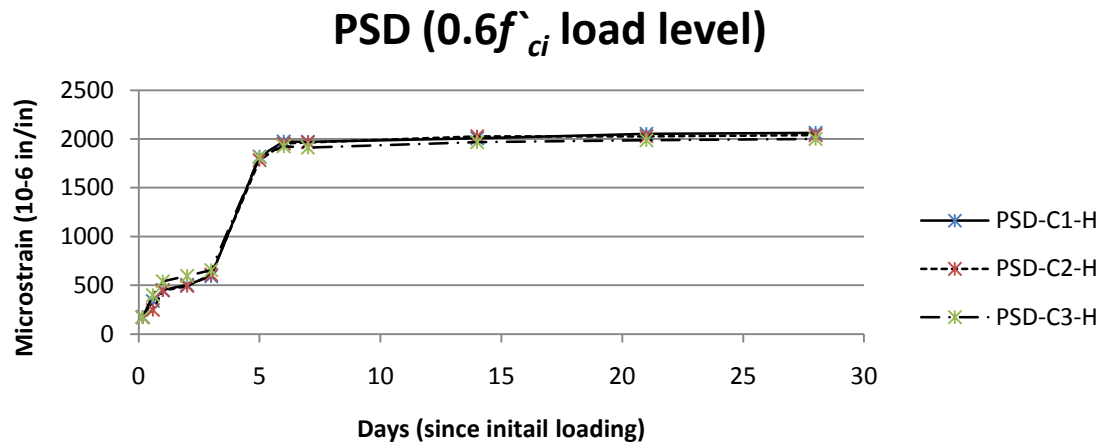


Figure D.4 PSD creep and shrinkage strains

Table D.13
PSD initial strain data for creep specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Delayed Cure (PSD)

Date: 7/19/11

Comp1: 98850

Comp2: 96700

UHPC Density (pcf): _____

Time: 11:30 AM

Comp3: 93580

	Cylinder ID	Cylinder Weight (lb)	Diameter			Total Length (in)			Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured	Avg		Measured	Avg							Measured	Avg
Creep Specimens	PSD-C1-H	7.78	Φ ₁	3.0075	3.0018	L ₁	11.9875	11.9858	7.0772	G _{ib1}	0.2593	G _{ia1}	0.2739	1826	1683
			Φ ₂	2.9985		L ₂	11.9845			G _{ib2}	0.2569	G _{ia2}	0.2709	1751	
			Φ ₃	2.9995		L ₃	11.9855			G _{ib3}	0.2398	G _{ia3}	0.2516	1473	
	PSD-C2-H	7.82	Φ ₁	3.0105	3.0070	L ₁	11.9855	11.9892	7.1016	G _{ib1}	0.2575	G _{ia1}	0.2726	1889	1450
			Φ ₂	3.0065		L ₂	11.9905			G _{ib2}	0.2486	G _{ia2}	0.2583	1212	
			Φ ₃	3.0040		L ₃	11.9915			G _{ib3}	0.2491	G _{ia3}	0.2591	1249	
	PSD-C3-H	7.77	Φ ₁	2.9960	2.9957	L ₁	11.9910	11.9882	7.0482	G _{ib1}	0.2305	G _{ia1}	0.2401	1197	1494
			Φ ₂	2.9970		L ₂	11.9835			G _{ib2}	0.2494	G _{ia2}	0.2645	1887	
			Φ ₃	2.9940		L ₃	11.9900			G _{ib3}	0.2445	G _{ia3}	0.2557	1398	
	PSD-C4-L	7.84	Φ ₁	3.0040	3.0015	L ₁	11.9895	11.9923	7.0756	G _{ib1}	0.2482	G _{ia1}	0.2537	687	433
			Φ ₂	3.0020		L ₂	11.9900			G _{ib2}	0.2491	G _{ia2}	0.2510	237	
			Φ ₃	2.9985		L ₃	11.9975			G _{ib3}	0.2510	G _{ia3}	0.2540	375	
	PSD-C5-L	7.84	Φ ₁	3.0100	3.0073	L ₁	11.9935	11.9902	7.1032	G _{ib1}	0.2541	G _{ia1}	0.2587	575	500
			Φ ₂	3.0050		L ₂	11.9895			G _{ib2}	0.2501	G _{ia2}	0.2549	600	
			Φ ₃	3.0070		L ₃	11.9875			G _{ib3}	0.2509	G _{ia3}	0.2535	325	
	PSD-C6-L	7.77	Φ ₁	2.9935	2.9963	L ₁	11.9925	11.9933	7.0513	G _{ib1}	0.2500	G _{ia1}	0.2557	712	646
			Φ ₂	3.0010		L ₂	11.9935			G _{ib2}	0.2546	G _{ia2}	0.2616	875	
			Φ ₃	2.9945		L ₃	11.9940			G _{ib3}	0.2549	G _{ia3}	0.2577	350	

Table D.14
PSD initial data for shrinkage specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Delayed Cure (PSD)

Date: 7/19/11

Comp1: 98850

Comp2: 96700

UHPC Density (pcf): _____

Time: 11:30 AM

Comp3: 93580

	Cylinder ID	Cylinder Weight (lb)	Diameter		Avg	Total Length (in)		Avg	Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured			Measured								Measured	Avg
Shrinkage Specimens	PSD-S1	7.72	Φ ₁	3.0095	3.0002	L ₁	11.9810	11.9865	7.0694	G _{ib1}	0.2579	G _{ia1}			
			Φ ₂	2.9925		L ₂	11.9920			G _{ib2}	0.2451	G _{ia2}			
			Φ ₃	2.9985		L ₃	11.9865			G _{ib3}	0.2401	G _{ia3}			
	PSD-S2	7.74	Φ ₁	3.0020	2.9990	L ₁	11.9940	11.9958	7.0639	G _{ib1}	0.2528	G _{ia1}			
			Φ ₂	2.9970		L ₂	11.9965			G _{ib2}	0.2419	G _{ia2}			
			Φ ₃	2.9980		L ₃	11.9970			G _{ib3}	0.2499	G _{ia3}			
	PSD-S3	7.83	Φ ₁	2.9960	2.9948	L ₁	12.0090	11.9988	7.0443	G _{ib1}	0.2595	G _{ia1}			
			Φ ₂	2.9935		L ₂	11.9915			G _{ib2}	0.2397	G _{ia2}			
			Φ ₃	2.9950		L ₃	11.9960			G _{ib3}	0.2550	G _{ia3}			

Table D.15
PSD creep measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: _____ Pre-steam Delay _____ (PSD) _____

	Cylin der ID	Date: 7-19-11 Gage Length Reading, 4hr (in)		Date: 7-19-11 Gage Length Reading, 14hr (in)		Date: 7-20-11 Gage Length Reading, Day 1 (in)		Date: 7-21-11 Gage Length Reading, Day 2 (in)		Date: 7-22-11 Gage Length Reading, Day 3 (in)		Date: 7-24-11 Gage Length Reading, Day 5 (in)		Date: 7-25-11 Gage Length Reading, Day 6 (in)		Date: 7-16-11 Gage Length Reading, Day 7 (in)		Date: 8-2-11 Gage Length Reading, Day 14 (in)	
Creep Specimens	PSD- C1-H	G _{4h-1}	0.2754	G _{14h-1}	0.2769	G _{1d-1}	0.278	G _{2d-1}	0.279	G _{3d-1}	0.2796	G _{4d-1}	0.2905	G _{5d-1}	0.2919	G _{6d-1}	0.2918	G _{7d-1}	0.2923
		G _{4h-2}	0.2723	G _{14h-2}	0.2731	G _{1d-2}	0.2737	G _{2d-2}	0.2738	G _{3d-2}	0.2745	G _{4d-2}	0.2826	G _{5d-2}	0.2839	G _{6d-2}	0/2839	G _{7d-2}	0.2839
		G _{4h-3}	0.2529	G _{14h-3}	0.2545	G _{1d-3}	0.2555	G _{2d-3}	0.2557	G _{3d-3}	0.2565	G _{4d-3}	0.2669	G _{5d-3}	0.2679	G _{6d-3}	0.2679	G _{7d-3}	0.2683
	PSD- C2-H	G _{4h-1}	0.2743	G _{14h-1}	0.274	G _{1d-1}	0.2769	G _{2d-1}	0.2775	G _{3d-1}	0.2783	G _{4d-1}	0.2887	G _{5d-1}	0.2905	G _{6d-1}	0.2905	G _{7d-1}	0.2910
		G _{4h-2}	0.2593	G _{14h-2}	0.2603	G _{1d-2}	0.2614	G _{2d-2}	0.2617	G _{3d-2}	0.263	G _{4d-2}	0.273	G _{5d-2}	0.2742	G _{6d-2}	0.2744	G _{7d-2}	0.2750
		G _{4h-3}	0.2605	G _{14h-3}	0.2616	G _{1d-3}	0.2624	G _{2d-3}	0.2626	G _{3d-3}	0.2633	G _{4d-3}	0.271	G _{5d-3}	0.2721	G _{6d-3}	0.2722	G _{7d-3}	0.2726
	PSD- C3-H	G _{4h-1}	0.2411	G _{14h-1}	0.2437	G _{1d-1}	0.2446	G _{2d-1}	0.245	G _{3d-1}	0.2452	G _{4d-1}	0.254	G _{5d-1}	0.255	G _{6d-1}	0.2550	G _{7d-1}	0.2554
		G _{4h-2}	0.2662	G _{14h-2}	0.2673	G _{1d-2}	0.2683	G _{2d-2}	0.2689	G _{3d-2}	0.2698	G _{4d-2}	0.2795	G _{5d-2}	0.28	G _{6d-2}	0.2801	G _{7d-2}	0.2804
		G _{4h-3}	0.2571	G _{14h-3}	0.2589	G _{1d-3}	0.2604	G _{2d-3}	0.2607	G _{3d-3}	0.261	G _{4d-3}	0.2703	G _{5d-3}	0.2715	G _{6d-3}	0.2711	G _{7d-3}	0.2717
	PSD- C4-L	G _{4h-1}	0.2542	G _{14h-1}	0.255	G _{1d-1}	0.2556	G _{2d-1}	0.2557	G _{3d-1}	0.2558	G _{4d-1}	0.2587	G _{5d-1}	0.2601	G _{6d-1}	0.2601	G _{7d-1}	0.2604
		G _{4h-2}	0.252	G _{14h-2}	0.2523	G _{1d-2}	0.2526	G _{2d-2}	0.2528	G _{3d-2}	0.2531	G _{4d-2}	0.2555	G _{5d-2}	0.2566	G _{6d-2}	0.2568	G _{7d-2}	0.2569
		G _{4h-3}	0.2544	G _{14h-3}	0.2549	G _{1d-3}	0.2556	G _{2d-3}	0.2556	G _{3d-3}	0.2556	G _{4d-3}	0.258	G _{5d-3}	0.2592	G _{6d-3}	0.2592	G _{7d-3}	0.2596
	PSD- C5-L	G _{4h-1}	0.2594	G _{14h-1}	0.2595	G _{1d-1}	0.2595	G _{2d-1}	0.2593	G _{3d-1}	0.2596	G _{4d-1}	0.263	G _{5d-1}	0.2639	G _{6d-1}	0.2641	G _{7d-1}	0.2641
		G _{4h-2}	0.2555	G _{14h-2}	0.2568	G _{1d-2}	0.2577	G _{2d-2}	0.258	G _{3d-2}	0.258	G _{4d-2}	0.2614	G _{5d-2}	0.2627	G _{6d-2}	0.2627	G _{7d-2}	0.2630
		G _{4h-3}	0.254	G _{14h-3}	0.2546	G _{1d-3}	0.2551	G _{2d-3}	0.2552	G _{3d-3}	0.2555	G _{4d-3}	0.2576	G _{5d-3}	0.2586	G _{6d-3}	0.2588	G _{7d-3}	0.2590
	PSD- C6-L	G _{4h-1}	0.256	G _{14h-1}	0.2568	G _{1d-1}	0.2575	G _{2d-1}	0.2577	G _{3d-1}	0.2578	G _{4d-1}	0.2605	G _{5d-1}	0.2614	G _{6d-1}	0.2615	G _{7d-1}	0.2617
		G _{4h-2}	0.262	G _{14h-2}	0.2625	G _{1d-2}	0.2629	G _{2d-2}	0.2631	G _{3d-2}	0.2632	G _{4d-2}	0.2663	G _{5d-2}	0.2672	G _{6d-2}	0.2672	G _{7d-2}	0.2673
		G _{4h-3}	0.2581	G _{14h-3}	0.2591	G _{1d-3}	0.2599	G _{2d-3}	0.26	G _{3d-3}	0.2602	G _{4d-3}	0.2627	G _{5d-3}	0.2638	G _{6d-3}	0.2638	G _{7d-3}	0.2642

Table D.15, continued

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Presteam Delay (PST)

	Cylinder ID	Date: 8-9-11 Gage Length Reading, Day 21 (in)		Date: 8-16-11 Gage Length Reading, Day 28 (in)	
Creep Specimens	PSD-C1-H	G _{2w-1}	0.2926	G _{3w-1}	0.2927
		G _{2w-2}	0.2840	G _{3w-2}	0.2840
		G _{2w-3}	0.2690	G _{3w-3}	0.2691
	PSD-C2-H	G _{2w-1}	0.2910	G _{3w-1}	0.2912
		G _{2w-2}	0.2749	G _{3w-2}	0.2749
		G _{2w-3}	0.2727	G _{3w-3}	0.2728
	PSD-C3-H	G _{2w-1}	0.2556	G _{3w-1}	0.2557
		G _{2w-2}	0.2806	G _{3w-2}	0.2807
		G _{2w-3}	0.2718	G _{3w-3}	0.2719
	PSD-C4-L	G _{2w-1}	0.2605	G _{3w-1}	0.2606
		G _{2w-2}	0.2570	G _{3w-2}	0.2570
		G _{2w-3}	0.2598	G _{3w-3}	0.2599
	PSD-C5-L	G _{2w-1}	0.2642	G _{3w-1}	0.2641
		G _{2w-2}	0.2631	G _{3w-2}	0.2631
		G _{2w-3}	0.2590	G _{3w-3}	0.2590
	PSD-C6-L	G _{2w-1}	0.2618	G _{3w-1}	0.2619
		G _{2w-2}	0.2675	G _{3w-2}	0.2675
		G _{2w-3}	0.2645	G _{3w-3}	0.2643

Table D.16
PSD shrinkage measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: _____ Pre-steam Delay _____ (PSD) _____

	Cylinder ID	Date: 7-19-11 Gage Length Reading, 4hr (in)		Date: 7-19-11 Gage Length Reading, 14hr (in)		Date: 7-20-11 Gage Length Reading, Day 1 (in)		Date: 7-21-11 Gage Length Reading, Day 2 (in)		Date: 7-22-11 Gage Length Reading, Day 3 (in)		Date: 7-24-11 Gage Length Reading, Day 5 (in)		Date: 7-25-11 Gage Length Reading, Day 6 (in)		Date: 7-16-11 Gage Length Reading, Day 7 (in)		Date: 8-2-11 Gage Length Reading, Day 14 (in)	
Shrinkage Specimens	PSD-S1	G _{4h-1}	0.2587	G _{14h-1}	0.259	G _{1d-1}	0.2592	G _{2d-1}	0.2592	G _{3d-1}	0.2593	G _{4d-1}	0.2597	G _{5d-1}	0.2603	G _{6d-1}	0.2603	G _{7d-1}	0.2605
		G _{4h-2}	0.2459	G _{14h-2}	0.2461	G _{1d-2}	0.2462	G _{2d-2}	0.2465	G _{3d-2}	0.2465	G _{4d-2}	0.2469	G _{5d-2}	0.2472	G _{6d-2}	0.2472	G _{7d-2}	0.2475
		G _{4h-3}	0.2406	G _{14h-3}	0.2405	G _{1d-3}	0.2409	G _{2d-3}	0.241	G _{3d-3}	0.2409	G _{4d-3}	0.2413	G _{5d-3}	0.2416	G _{6d-3}	0.2417	G _{7d-3}	0.2419
	PSD-S2	G _{4h-1}	0.2535	G _{14h-1}	0.2537	G _{1d-1}	0.2539	G _{2d-1}	0.254	G _{3d-1}	0.2539	G _{4d-1}	0.2545	G _{5d-1}	0.2548	G _{6d-1}	0.2548	G _{7d-1}	0.2551
		G _{4h-2}	0.2425	G _{14h-2}	0.2428	G _{1d-2}	0.2431	G _{2d-2}	0.2431	G _{3d-2}	0.2431	G _{4d-2}	0.2439	G _{5d-2}	0.2441	G _{6d-2}	0.2441	G _{7d-2}	0.2442
		G _{4h-3}	0.2505	G _{14h-3}	0.2508	G _{1d-3}	0.251	G _{2d-3}	0.2512	G _{3d-3}	0.2512	G _{4d-3}	0.2524	G _{5d-3}	0.2526	G _{6d-3}	0.2528	G _{7d-3}	0.2529
	PSD-S3	G _{4h-1}	0.2603	G _{14h-1}	0.2604	G _{1d-1}	0.2605	G _{2d-1}	0.2605	G _{3d-1}	0.2607	G _{4d-1}	0.2611	G _{5d-1}	0.2611	G _{6d-1}	0.2611	G _{7d-1}	0.2612
		G _{4h-2}	0.2405	G _{14h-2}	0.2408	G _{1d-2}	0.2409	G _{2d-2}	0.241	G _{3d-2}	0.241	G _{4d-2}	0.241	G _{5d-2}	0.2411	G _{6d-2}	0.2411	G _{7d-2}	0.2414
		G _{4h-3}	0.2553	G _{14h-3}	0.2556	G _{1d-3}	0.2558	G _{2d-3}	0.256	G _{3d-3}	0.2559	G _{4d-3}	0.2564	G _{5d-3}	0.2569	G _{6d-3}	0.2570	G _{7d-3}	0.2572

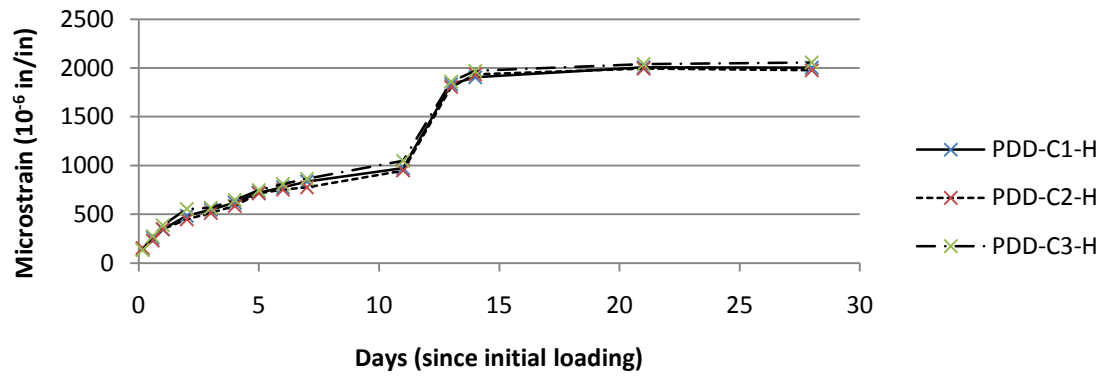
Table D.16, continued

UHPC Creep and Shrinkage Data Sheet

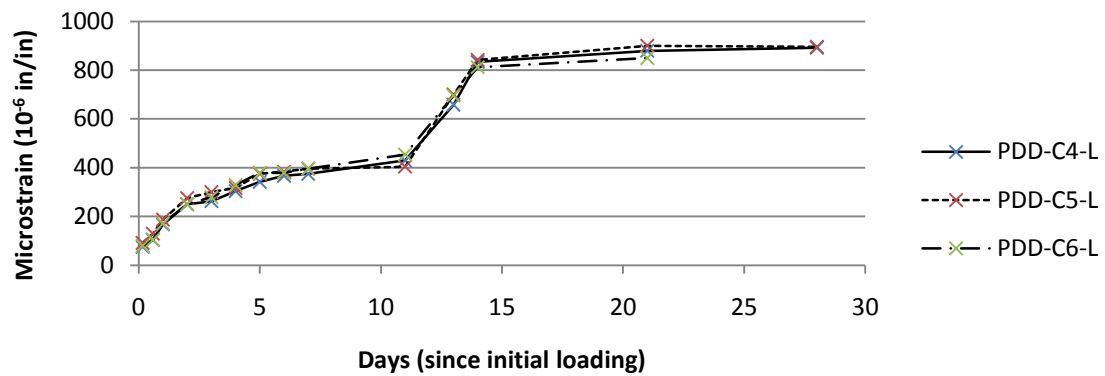
Curing Regime: Pre-steam Delay (PSD)

	Cylinder ID	Date: 8-9-11 Gage Length Reading, Day 21 (in)		Date: 8-16-11 Gage Length Reading, Day 28 (in)	
Shrinkage Specimens	PSD-S1	G _{2w-1}	0.2607	G _{3w-1}	0.2607
		G _{2w-2}	0.2475	G _{3w-2}	0.2476
		G _{2w-3}	0.2421	G _{3w-3}	0.2422
	PSD-S2	G _{2w-1}	0.2551	G _{3w-1}	0.2551
		G _{2w-2}	0.2442	G _{3w-2}	0.2442
		G _{2w-3}	0.2530	G _{3w-3}	0.2530
	PSD-S3	G _{2w-1}	0.2613	G _{3w-1}	0.2615
		G _{2w-2}	0.2417	G _{3w-2}	0.2418
		G _{2w-3}	0.2576	G _{3w-3}	0.2575

PDD (0.6*f_{ci}* load level)



PDD (0.2*f_{ci}* load level)



PDD Shrinkage Specimens

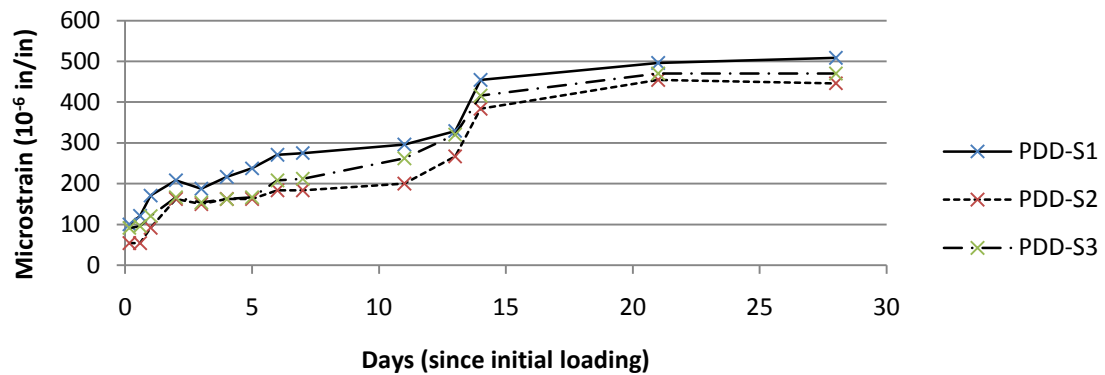


Figure D.5 PDD creep and shrinkage strains

Table D.17
PDD initial strain data for creep specimens

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Double Delay (PDD)

Date: 7-13-11

Comp1: 79200

Comp2: 105400

UHPC Density (pcf): _____

Time: 11:00 AM

Comp3: 99500

	Cylinder ID	Cylinder Weight (lb)	Diameter		Avg	Total Length (in)		Avg	Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured			Measured				Measured		Measured		Measured	Avg
Creep Specimens	PDD-C1-H	7.84	Φ ₁	2.9980	3.0010	L ₁	11.9765	11.9803	7.0733	G _{ib1}	0.2519	G _{ia1}	0.2671	1900	1542
			Φ ₂	3.0035		L ₂	11.9840			G _{ib2}	0.2500	G _{ia2}	0.2611	1387	
			Φ ₃	3.0015		L ₃	11.9805			G _{ib3}	0.2618	G _{ia3}	0.2725	1339	
	PDD-C2-H	7.8	Φ ₁	3.0060	3.0018	L ₁	11.9720	11.9713	7.0772	G _{ib1}	0.2623	G _{ia1}	0.2778	1940	1602
			Φ ₂	2.9980		L ₂	11.9760			G _{ib2}	0.2607	G _{ia2}	0.2756	1864	
			Φ ₃	3.0015		L ₃	11.9660			G _{ib3}	0.2590	G _{ia3}	0.2670	1001	
	PDD-C3-H	7.82	Φ ₁	3.0340	3.0138	L ₁	11.9785	11.9780	7.1339	G _{ib1}	0.2515	G _{ia1}	0.2610	1187	1486
			Φ ₂	3.0035		L ₂	11.9795			G _{ib2}	0.2616	G _{ia2}	0.2720	1301	
			Φ ₃	3.0040		L ₃	11.9760			G _{ib3}	0.2357	G _{ia3}	0.2515	1971	
	PDD-C4-L	7.74	Φ ₁	3.0155	3.0057	L ₁	11.9655	11.9693	7.0953	G _{ib1}	0.2366	G _{ia1}	0.2398	399	604
			Φ ₂	2.9925		L ₂	11.9730			G _{ib2}	0.2596	G _{ia2}	0.2675	988	
			Φ ₃	3.0090		L ₃	11.9695			G _{ib3}	0.2529	G _{ia3}	0.2563	425	
	PDD-C5-L	7.87	Φ ₁	2.9950	2.9998	L ₁	11.9690	11.9693	7.0678	G _{ib1}	0.2512	G _{ia1}	0.2536	300	529
			Φ ₂	2.9955		L ₂	11.9735			G _{ib2}	0.2426	G _{ia2}	0.2510	1049	
			Φ ₃	3.0090		L ₃	11.9655			G _{ib3}	0.2598	G _{ia3}	0.2617	238	
	PDD-C6-L	7.84	Φ ₁	3.0035	3.0013	L ₁	11.9715	11.9762	7.0749	G _{ib1}	0.2484	G _{ia1}	0.2496	150	641
			Φ ₂	2.9925		L ₂	11.9800			G _{ib2}	0.2429	G _{ia2}	0.2528	1236	
			Φ ₃	3.0080		L ₃	11.9770			G _{ib3}	0.2525	G _{ia3}	0.2568	537	

Table D.18
PDD initial shrinkage data

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Double Delay (PDD)

Date: 7-13-11

Comp1: 79200

Comp2: 105400

UHPC Density (pcf): _____

Time: 11:00 AM

Comp3: 99500

	Cylinder ID	Cylinder Weight (lb)	Diameter		Avg	Total Length (in)		Avg	Average Area (in ²)	Initial Gage Length Before Loading (in)		Initial Gage Length After Loading (in)		Initial Elastic Strain	
			Measured			Measured								Measured	Avg
Shrinkage Specimens	PDD-S1	7.74	Φ ₁	3.0040	2.9990	L ₁	11.9775	11.9793	7.0639	G _{ib1}	0.2594	G _{ia1}			
			Φ ₂	2.9975		L ₂	11.9810			G _{ib2}	0.2617	G _{ia2}			
			Φ ₃	2.9955		L ₃	11.9795			G _{ib3}	0.2505	G _{ia3}			
	PDD-S2	7.75	Φ ₁	3.0055	3.0058	L ₁	11.9905	11.9878	7.0961	G _{ib1}	0.2547	G _{ia1}			
			Φ ₂	2.9980		L ₂	11.9885			G _{ib2}	0.2653	G _{ia2}			
			Φ ₃	3.0140		L ₃	11.9845			G _{ib3}	0.2597	G _{ia3}			
	PDD-S3	7.73	Φ ₁	3.0015	3.0002	L ₁	11.9895	11.9838	7.0694	G _{ib1}	0.2189	G _{ia1}			
			Φ ₂	2.9975		L ₂	11.9890			G _{ib2}	0.2456	G _{ia2}			
			Φ ₃	3.0015		L ₃	11.9730			G _{ib3}	0.2520	G _{ia3}			

Table D.19
PDD creep measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Double Delay (PDD)

	Cylinder ID	Date: 7-13-11 Gage Length Reading, 4hr (in)		Date: 7-13-11 Gage Length Reading, 14hr (in)		Date: 7-14-11 Gage Length Reading, Day 1 (in)		Date: 7-15-11 Gage Length Reading, Day 2 (in)		Date: 7-16-11 Gage Length Reading, Day 3 (in)		Date: 7-17-11 Gage Length Reading, Day 4 (in)		Date: 7-18-11 Gage Length Reading, Day 5 (in)		Date: 7-19-11 Gage Length Reading, Day 6 (in)		Date: 7-20-11 Gage Length Reading, Day 7 (in)	
142	PDD-C1-H	G _{4h-1}	0.2677	G _{14h-1}	0.269	G _{1d-1}	0.2698	G _{2d-1}	0.2712	G _{3d-1}	0.2718	G _{4d-1}	0.2724	G _{5d-1}	0.2732	G _{6d-1}	0.2736	G _{7d-1}	0.274
		G _{4h-2}	0.2625	G _{14h-2}	0.2632	G _{1d-2}	0.2635	G _{2d-2}	0.2642	G _{3d-2}	0.2646	G _{4d-2}	0.2649	G _{5d-2}	0.2658	G _{6d-2}	0.2658	G _{7d-2}	0.2658
		G _{4h-3}	0.2739	G _{14h-3}	0.2747	G _{1d-3}	0.2757	G _{2d-3}	0.2769	G _{3d-3}	0.2774	G _{4d-3}	0.2782	G _{5d-3}	0.279	G _{6d-3}	0.2799	G _{7d-3}	0.2809
	PDD-C2-H	G _{4h-1}	0.279	G _{14h-1}	0.2795	G _{1d-1}	0.2806	G _{2d-1}	0.2819	G _{3d-1}	0.2824	G _{4d-1}	0.283	G _{5d-1}	0.2841	G _{6d-1}	0.2846	G _{7d-1}	0.285
		G _{4h-2}	0.2768	G _{14h-2}	0.2774	G _{1d-2}	0.2787	G _{2d-2}	0.2788	G _{3d-2}	0.2793	G _{4d-2}	0.2798	G _{5d-2}	0.281	G _{6d-2}	0.281	G _{7d-2}	0.2811
		G _{4h-3}	0.2683	G _{14h-3}	0.269	G _{1d-3}	0.2694	G _{2d-3}	0.2704	G _{3d-3}	0.271	G _{4d-3}	0.2716	G _{5d-3}	0.2724	G _{6d-3}	0.2728	G _{7d-3}	0.2729
	PDD-C3-H	G _{4h-1}	0.2629	G _{14h-1}	0.2641	G _{1d-1}	0.2647	G _{2d-1}	0.2665	G _{3d-1}	0.2665	G _{4d-1}	0.2674	G _{5d-1}	0.2683	G _{6d-1}	0.2687	G _{7d-1}	0.2692
		G _{4h-2}	0.2728	G _{14h-2}	0.2739	G _{1d-2}	0.2753	G _{2d-2}	0.277	G _{3d-2}	0.2776	G _{4d-2}	0.2782	G _{5d-2}	0.279	G _{6d-2}	0.2794	G _{7d-2}	0.28
		G _{4h-3}	0.252	G _{14h-3}	0.2531	G _{1d-3}	0.2538	G _{2d-3}	0.2543	G _{3d-3}	0.254	G _{4d-3}	0.2544	G _{5d-3}	0.2551	G _{6d-3}	0.2558	G _{7d-3}	0.256
	PDD-C4-L	G _{4h-1}	0.2405	G _{14h-1}	0.2407	G _{1d-1}	0.2413	G _{2d-1}	0.2417	G _{3d-1}	0.2417	G _{4d-1}	0.2423	G _{5d-1}	0.2424	G _{6d-1}	0.2425	G _{7d-1}	0.2426
		G _{4h-2}	0.2681	G _{14h-2}	0.2684	G _{1d-2}	0.2688	G _{2d-2}	0.2694	G _{3d-2}	0.2696	G _{4d-2}	0.2699	G _{5d-2}	0.2704	G _{6d-2}	0.2706	G _{7d-2}	0.2707
		G _{4h-3}	0.2568	G _{14h-3}	0.257	G _{1d-3}	0.2576	G _{2d-3}	0.2585	G _{3d-3}	0.2586	G _{4d-3}	0.2583	G _{5d-3}	0.2590	G _{6d-3}	0.2593	G _{7d-3}	0.2593
	PDD-C5-L	G _{4h-1}	0.2542	G _{14h-1}	0.2545	G _{1d-1}	0.2549	G _{2d-1}	0.2555	G _{3d-1}	0.2559	G _{4d-1}	0.2559	G _{5d-1}	0.2565	G _{6d-1}	0.2563	G _{7d-1}	0.2565
		G _{4h-2}	0.2515	G _{14h-2}	0.252	G _{1d-2}	0.2524	G _{2d-2}	0.2532	G _{3d-2}	0.2542	G _{4d-2}	0.2534	G _{5d-2}	0.2539	G _{6d-2}	0.2542	G _{7d-2}	0.2543
		G _{4h-3}	0.2628	G _{14h-3}	0.2629	G _{1d-3}	0.2635	G _{2d-3}	0.2642	G _{3d-3}	0.2644	G _{4d-3}	0.2646	G _{5d-3}	0.2649	G _{6d-3}	0.2650	G _{7d-3}	0.2650
	PDD-C6-L	G _{4h-1}	0.2504	G _{14h-1}	0.2505	G _{1d-1}	0.2510	G _{2d-1}	0.2516	G _{3d-1}	0.2518	G _{4d-1}	0.2521	G _{5d-1}	0.2522	G _{6d-1}	0.2524	G _{7d-1}	0.2525
		G _{4h-2}	0.2534	G _{14h-2}	0.2536	G _{1d-2}	0.2539	G _{2d-2}	0.2545	G _{3d-2}	0.2546	G _{4d-2}	0.2550	G _{5d-2}	0.2554	G _{6d-2}	0.2554	G _{7d-2}	0.2557
		G _{4h-3}	0.2573	G _{14h-3}	0.2576	G _{1d-3}	0.2584	G _{2d-3}	0.2591	G _{3d-3}	0.2595	G _{4d-3}	0.2600	G _{5d-3}	0.2607	G _{6d-3}	0.2605	G _{7d-3}	0.2605

Table D.21, continued

UHPC Creep and Shrinkage Data SheetCuring Regime: Pre-steam Double Delay (PDD)

	Cylinder ID	Date: 7-24-11 Gage Length Reading, Before Cure (in)		Date: 7-26-11 Gage Length Reading, After Cure (in)		Date: 7-27-11 Gage Length Reading, Day 14 (in)		Date: 8-3-11 Gage Length Reading, Day 21 (in)		Date: 8-10-11 Gage Length Reading, Day 28 (in)	
Creep Specimens	PDD-C1-H	G _{2w-1}	0.274	G _{3w-1}	0.2823	G _{1d-1}	0.2839	G _{2d-1}	0.2842	G _{3d-1}	0.2842
		G _{2w-2}	0.2677	G _{3w-2}	0.2733	G _{1d-2}	0.2726	G _{2d-2}	0.2741	G _{3d-2}	0.2741
		G _{2w-3}	0.2823	G _{3w-3}	0.2890	G _{1d-3}	0.2898	G _{2d-3}	0.2905	G _{3d-3}	0.2904
	PDD-C2-H	G _{2w-1}	0.2863	G _{3w-1}	0.2942	G _{1d-1}	0.2956	G _{2d-1}	0.2961	G _{3d-1}	0.2958
		G _{2w-2}	0.2826	G _{3w-2}	0.2888	G _{1d-2}	0.2899	G _{2d-2}	0.2901	G _{3d-2}	0.2901
		G _{2w-3}	0.2742	G _{3w-3}	0.2806	G _{1d-3}	0.2812	G _{2d-3}	0.2819	G _{3d-3}	0.2818
	PDD-C3-H	G _{2w-1}	0.2705	G _{3w-1}	0.2773	G _{1d-1}	0.2782	G _{2d-1}	0.2788	G _{3d-1}	0.2792
		G _{2w-2}	0.2816	G _{3w-2}	0.2891	G _{1d-2}	0.2904	G _{2d-2}	0.2909	G _{3d-2}	0.2909
		G _{2w-3}	0.2575	G _{3w-3}	0.2627	G _{1d-3}	0.2631	G _{2d-3}	0.2637	G _{3d-3}	0.2637
	PDD-C4-L	G _{2w-1}	0.2423	G _{3w-1}	0.2442	G _{1d-1}	0.2457	G _{2d-1}	0.2458	G _{3d-1}	0.2460
		G _{2w-2}	0.2715	G _{3w-2}	0.2739	G _{1d-2}	0.2750	G _{2d-2}	0.2755	G _{3d-2}	0.2756
		G _{2w-3}	0.2601	G _{3w-3}	0.2613	G _{1d-3}	0.2629	G _{2d-3}	0.2634	G _{3d-3}	0.2634
	PDD-C5-L	G _{2w-1}	0.2565	G _{3w-1}	0.2586	G _{1d-1}	0.2594	G _{2d-1}	0.2599	G _{3d-1}	0.2598
		G _{2w-2}	0.2542	G _{3w-2}	0.2568	G _{1d-2}	0.2581	G _{2d-2}	0.2586	G _{3d-2}	0.2585
		G _{2w-3}	0.2653	G _{3w-3}	0.2677	G _{1d-3}	0.2690	G _{2d-3}	0.2694	G _{3d-3}	0.2595
	PDD-C6-L	G _{2w-1}	0.253	G _{3w-1}	0.2545	G _{1d-1}	0.2552	G _{2d-1}	0.2555	G _{3d-1}	0.2556
		G _{2w-2}	0.2561	G _{3w-2}	0.2580	G _{1d-2}	0.2593	G _{2d-2}	0.2597	G _{3d-2}	0.2596
		G _{2w-3}	0.261	G _{3w-3}	0.2634	G _{1d-3}	0.2642	G _{2d-3}	0.2644	G _{3d-3}	0.2644

Table D.20
PDD shrinkage measurements

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Double Delay (PDD)

	Cylinder ID	Date: 7-13-11 Gage Length Reading, 4hr (in)		Date: 7-13-11 Gage Length Reading, 14hr (in)		Date: 7-14-11 Gage Length Reading, Day 1 (in)		Date: 7-15-11 Gage Length Reading, Day 2 (in)		Date: 7-16-11 Gage Length Reading, Day 3 (in)		Date: 7-17-11 Gage Length Reading, Day 4 (in)		Date: 7-18-11 Gage Length Reading, Day 5 (in)		Date: 7-19-11 Gage Length Reading, Day 6 (in)		Date: 7-20-11 Gage Length Reading, Day 7 (in)	
		G _{4h-1}		G _{14h-1}		G _{1d-1}		G _{2d-1}		G _{3d-1}		G _{4d-1}		G _{5d-1}		G _{6d-1}		G _{7d-1}	
Shrinkage Specimens	PDD-S1	G _{4h-2}	0.2598	G _{14h-2}	0.26	G _{1d-2}	0.2606	G _{2d-2}	0.261	G _{3d-2}	0.2607	G _{4d-2}	0.261	G _{5d-2}	0.2611	G _{6d-2}	0.2614	G _{7d-2}	0.2615
		G _{4h-3}	0.2631	G _{14h-3}	0.2632	G _{1d-3}	0.2633	G _{2d-3}	0.2636	G _{3d-3}	0.2637	G _{4d-3}	0.2638	G _{5d-3}	0.264	G _{6d-3}	0.2642	G _{7d-3}	0.2642
		G _{4h-1}	0.2511	G _{14h-1}	0.2513	G _{1d-1}	0.2518	G _{2d-1}	0.252	G _{3d-1}	0.2517	G _{4d-1}	0.252	G _{5d-1}	0.2522	G _{6d-1}	0.2525	G _{7d-1}	0.2525
	PDD-S2	G _{4h-2}	0.255	G _{14h-2}	0.2549	G _{1d-2}	0.2551	G _{2d-2}	0.2556	G _{3d-2}	0.2557	G _{4d-2}	0.2557	G _{5d-2}	0.2557	G _{6d-2}	0.2557	G _{7d-2}	0.2557
		G _{4h-3}	0.2662	G _{14h-3}	0.2661	G _{1d-3}	0.2665	G _{2d-3}	0.2671	G _{3d-3}	0.2671	G _{4d-3}	0.267	G _{5d-3}	0.267	G _{6d-3}	0.2673	G _{7d-3}	0.2672
		G _{4h-1}	0.2598	G _{14h-1}	0.26	G _{1d-1}	0.2603	G _{2d-1}	0.2609	G _{3d-1}	0.2605	G _{4d-1}	0.2609	G _{5d-1}	0.2609	G _{6d-1}	0.2611	G _{7d-1}	0.2612
	PDD-S3	G _{4h-2}	0.2198	G _{14h-2}	0.2197	G _{1d-2}	0.22	G _{2d-2}	0.2204	G _{3d-2}	0.2204	G _{4d-2}	0.2204	G _{5d-2}	0.2205	G _{6d-2}	0.2209	G _{7d-2}	0.221
		G _{4h-3}	0.2465	G _{14h-3}	0.2465	G _{1d-3}	0.2466	G _{2d-3}	0.2469	G _{3d-3}	0.2468	G _{4d-3}	0.2469	G _{5d-3}	0.2467	G _{6d-3}	0.2472	G _{7d-3}	0.2472
		G _{4h-1}	0.2524	G _{14h-1}	0.2526	G _{1d-1}	0.2528	G _{2d-1}	0.2532	G _{3d-1}	0.253	G _{4d-1}	0.2531	G _{5d-1}	0.2533	G _{6d-1}	0.2534	G _{7d-1}	0.2534

Table D.21, continued

UHPC Creep and Shrinkage Data Sheet

Curing Regime: Pre-steam Double Delay (PDD)

	Cylinder ID	Date: 7-24-11 Gage Length Reading, Before Cure (in)		Date: 7-26-11 Gage Length Reading, After Cure (in)		Date: 7-27-11 Gage Length Reading, Day 14 (in)		Date: 8-3-11 Gage Length Reading, Day 21 (in)		Date: 8-10-11 Gage Length Reading, Day 28 (in)	
Shrinkage Specimens	PDD-S1	G _{2w-1}	0.2616	G _{3w-1}	0.2618	G _{1d-1}	0.2628	G _{2d-1}	0.2634	G _{3d-1}	0.2634
		G _{2w-2}	0.2642	G _{3w-2}	0.2646	G _{1d-2}	0.2656	G _{2d-2}	0.2660	G _{3d-2}	0.2661
		G _{2w-3}	0.2529	G _{3w-3}	0.2531	G _{1d-3}	0.2541	G _{2d-3}	0.2541	G _{3d-3}	0.2534
	PDD-S2	G _{2w-1}	0.2557	G _{3w-1}	0.2563	G _{1d-1}	0.2570	G _{2d-1}	0.2578	G _{3d-1}	0.2577
		G _{2w-2}	0.2672	G _{3w-2}	0.2678	G _{1d-2}	0.2690	G _{2d-2}	0.2694	G _{3d-2}	0.2693
		G _{2w-3}	0.2616	G _{3w-3}	0.2620	G _{1d-3}	0.2629	G _{2d-3}	0.2634	G _{3d-3}	0.2634
	PDD-S3	G _{2w-1}	0.2212	G _{3w-1}	0.2216	G _{1d-1}	0.2220	G _{2d-1}	0.2227	G _{3d-1}	0.2227
		G _{2w-2}	0.2476	G _{3w-2}	0.2481	G _{1d-2}	0.2429	G _{2d-2}	0.2495	G _{3d-2}	0.2495
		G _{2w-3}	0.254	G _{3w-3}	0.2545	G _{1d-3}	0.2553	G _{2d-3}	0.2556	G _{3d-3}	0.2556

Appendix E - Modulus of Elasticity Checks

Table E.1
AMC modulus of elasticity check

Modulus of Elasticity Calculations for the Ambient Curing Regime (AMC)							
Specimen ID	Compressive Stress (kips)	Area (in ²)	Compressive Strength (ksi)	Initial Length Change ($L_i/\Delta L$)	Modulus of Elasticity (ksi)	Strength/Modulus Relationships	
AMC-C1-H	17.3	7.0686	12.2	1715	4197	ACI Norm	7034
AMC-C2-H	17.3	7.0725	12.2	1928	4716	ACI High Str	5418
AMC-C3-H	17.3	7.0811	12.2	2111	5158	Setra	6031
AMC-C4-L	51.8	7.0333	12.2	813	5986	Kakizaki	4856
AMC-C5-L	51.8	7.0568	12.2	842	6182	Sritharan	5523
AMC-C6-L	51.8	7.0427	12.2	776	5707	Kollmorgen	7026
Average Modulus of Elasticity					5324	Graybeal	5103

L_i is the average initial gage length before the compressive load is applied

ΔL is the average change in length immediately following the compressive load on the specimens

* Note: For the AMC Curing Regime, due to the data acquisition specimens with the "L" nomenclature were subjected to the stress level

Table E.2
SST modulus of elasticity check

Modulus of Elasticity Calculations for the Ambient Curing Regime (SST)							
Specimen ID	Compressive Stress (kips)	Area (in ²)	Compressive Strength (ksi)	Initial Length Change (L _i /ΔL)	Modulus of Elasticity (ksi)	Strength/Modulus Relationships	
SST-C1-H	59.67	7.0819	13.3	702	5916	ACI Norm	7344
SST-C2-H	59.67	7.0694	13.3	678	5719	ACI High Str	5613
SST-C3-H	59.67	7.0654	13.3	635	5360	Setra	6208
SST-C4-L	19.57	7.0584	13.3	1988	5513	Kakizaki	5070
SST-C5-L	19.57	7.0560	13.3	1984	5503	Sritharan	5766
SST-C6-L	19.57	7.0380	13.3	2197	6108	Kollmorgen	7222
<i>Average Modulus of Elasticity</i>					5686	Graybeal	5328

L_i is the average initial gage length before the compressive load is applied

ΔL is the average change in length immediately following the compressive load on the specimens

Table E.3
PST modulus of elasticity check

Modulus of Elasticity Calculations for the Ambient Curing Regime (AMC)							
Specimen ID	Compressive Stress (kips)	Area (in ²)	Compressive Strength (ksi)	Initial Length Change (L _i /ΔL)	Modulus of Elasticity (ksi)	Strength/Modulus Relationships	
PST-C1-H	58.6	7.0937	13.8	599	4950	ACI Norm	7481
PST-C2-H	58.6	7.0882	13.8	718	5939	ACI High Str	5699
PST-C3-H	58.6	7.0702	13.8	694	5749	Setra	6284
PST-C4-L	19.5	7.0827	13.8	2779	7650	Kakizaki	5164
PST-C5-L	19.5	7.0686	13.8	2161	5962	Sritharan	5874
PST-C6-L	19.5	7.0662	13.8	1801	4970	Kollmorgen	7307
<i>Average Modulus of Elasticity</i>					5860	Graybeal	5427

Table E.4
PSD modulus of elasticity check

Modulus of Elasticity Calculations for the Ambient Curing Regime (PSD)							
Specimen ID	Compressive Stress (kips)	Area (in²)	Compressive Strength (ksi)	Initial Length Change ($L_i/\Delta L$)	Modulus of Elasticity (ksi)	Strength/Modulus Relationships	
PDS-C1-H	57.8	7.0772	13.58	599	4906	ACI Norm	7421
PDS-C2-H	57.8	7.1016	13.58	718	6048	ACI High Str	5661
PDS-C3-H	57.8	7.0481	13.58	694	5913	Setra	6251
PDS-C4-L	19.2	7.0756	13.58	2779	7540	Kakizaki	5123
PDS-C5-L	19.2	7.1032	13.58	2161	5842	Sritharan	5826
PDS-C6-L	19.2	7.0513	13.58	1801	4904	Kollmorgen	7269
<i>Average Modulus of Elasticity</i>					5786	Graybeal	5384

L_i is the average initial gage length before the compressive load is applied

ΔL is the average change in length immediately following the compressive load on the specimens

Table E.5
PDD modulus of elasticity check

Modulus of Elasticity Calculations for the Ambient Curing Regime (PDD)							
Specimen ID	Compressive Stress (kips)	Area (in²)	Compressive Strength (ksi)	Initial Length Change ($L_i/\Delta L$)	Modulus of Elasticity (ksi)	Strength/Modulus Relationships	
PDD-C1-H	56.9	7.0733	13.4	665	5348	ACI Norm	7372
PDD-C2-H	56.9	7.0772	13.4	684	5497	ACI High Str	5630
PDD-C3-H	56.9	7.1339	13.4	626	4993	Setra	6223
PDD-C4-L	19.0	7.0953	13.4	1957	5240	Kakizaki	5089
PDD-C5-L	19.0	7.0678	13.4	2832	7612	Sritharan	5788
PDD-C6-L	19.0	7.0749	13.4	3113	8361	Kollmorgen	7239
<i>Average Modulus of Elasticity</i>					6175	Graybeal	5348

Appendix F - Creep Frames Under Thermal Cure

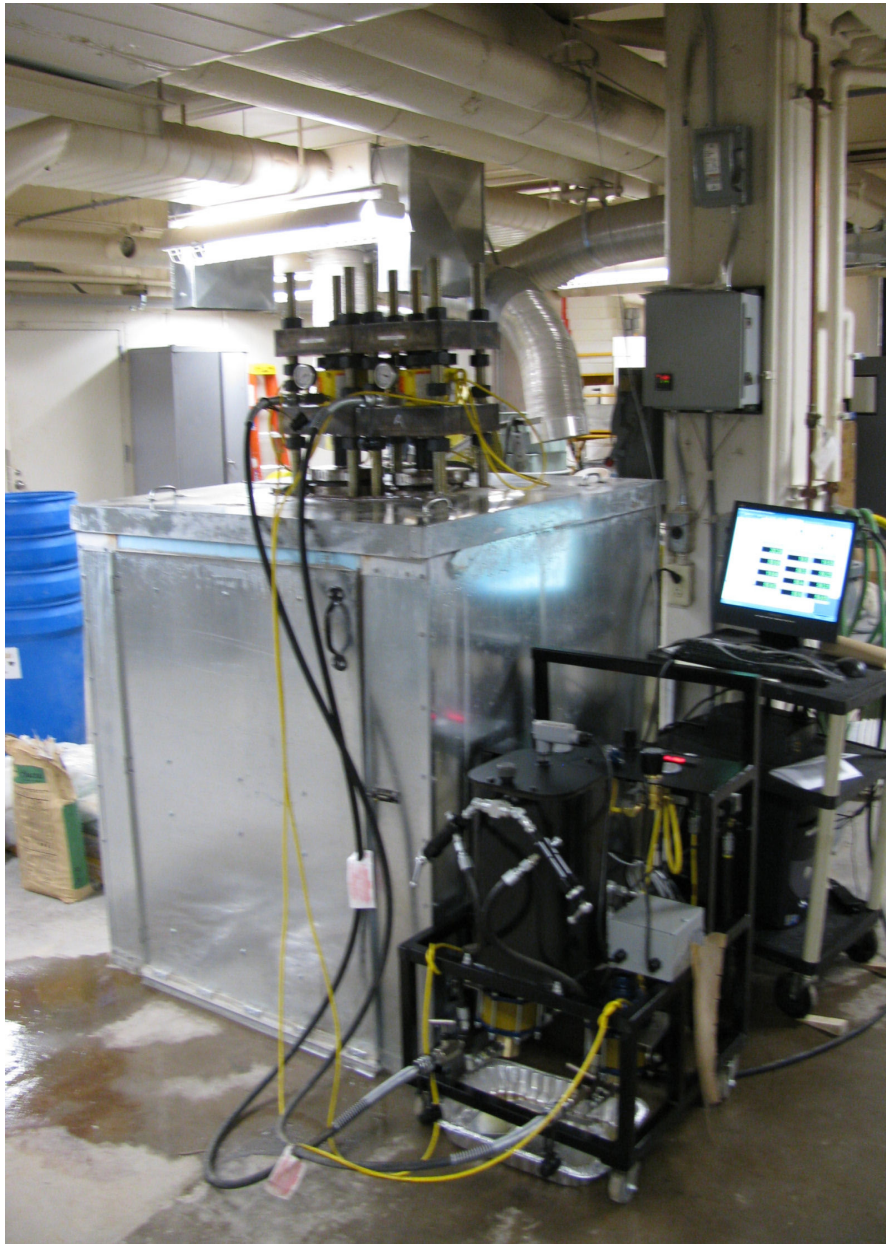


Figure F.1 Compressive specimens undergoing thermal cure