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REVIEW AND SPECIFICATION FOR SHRINKAGE CRACKS OF BRIDGE DECKS

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16. Abstract

An existing standard method ASTM C157 is used to determine the length change or free shrinkage of an unrestrained concrete specimen. However, in bridge decks, the concrete is actually under restrained conditions, and thus free shrinkage test methods do not represent the same condition of bridge decks and are not correlated to in-field bridge deck shrinkage. An alternative for restrained shrinkage is to use one of the two existing standards AASHTO T334-08 or ASTM C1581. In these two restrained test methods, the concrete is cast in the circumference around an inner steel ring.

The purpose of this study was to construct the apparatus for the AASHTO T334-08 method to estimate the cracking age of concrete mixtures that may be used in bridge decks. In the processes of the apparatus setup, several limitations to the method were discovered, such as the influence of the surrounding environment and the repeatability of the method. Thus, an additional study was done to evaluate the sensitivity of shrinkage measurements (ASTM C157 and AASHTO T334-08) in different surrounding environments, with different mix designs (e.g., varying w/cm, binder content and aggregate size), and different concrete specimen thicknesses. Overall, it was confirmed that most mixtures did not even indicate any cracking unless a high cement volume content of 24% with no coarse aggregates was tested using the existing AASHTO T334-08 restrained ring method. A thinner ring (2” of concrete instead of 3”) had a decreased age of cracking. The free shrinkage ASTM C157 is still the easiest, and a relatively fast method to use and can provide relative comparisons between different mixtures or between different environments.

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EXECUTIVE SUMMARY

The shrinkage in concrete, whether free or restrained, was found to mostly depend on the surrounding environment. The ASTM C157 free shrinkage test on concrete is more favorable than the AASHTO T334-08 ring shrinkage test. The free shrinkage can be easily correlated to time and different concrete mixtures but the AASHTO retrained method lacked a definitive cracking age and the results of the test depend largely on the strain gauges. It was also difficult to correlate restrained shrinkage to the mixture design due to the high variability in cracking age. The free shrinkage test cannot be used to predict the restrained shrinkage of specimens. Thus, a correlation between the age of cracking of the restrained bridge decks is still needed. Any future shrinkage testing should be performed on samples placed in a highly controlled environment in order to eliminate the environment.

1.0 INTRODUCTION

1.1 Problem Statement

There are a significant amount of bridge decks with cracking, including some made with internal curing, polymer-modified materials, or fiber-reinforced concrete. It is important to have a test procedure to verify whether the material itself can withstand the shrinkage strains particularly associated with restraint created by the underlying structure. The existing standard free shrinkage bar test is not sufficient to capture the restraint-created shrinkage. Without a restrained shrinkage test, any potential materials used for such structures could never be properly characterized to determine if it can withstand such cracking. There needs to be a better way to characterize materials used on bridge decks to determine reduced shrinkage cracking due to deck restraint.

1.2 Objectives

The primary objectives of this research project are to 1) recommended a test procedure to evaluate bridge deck materials, and 2) assist UDOT to build restrained shrinkage test apparatus that could be used to evaluate commonly-used bridge deck materials for restrained shrinkage performance.

1.3 Scope

A restrained ring shrinkage apparatus based on the AASHTO T334-08 standard was selected and the components purchased by UDOT. This apparatus was put together by the University of Utah at the UDOT Central Materials Facility. Some initial mixtures were created and used in this phase of the project in order to verify that the apparatus is functioning properly and to attempt to show the range of the system capabilities. This initial test method, the AASHTO T334-08, was selected by UDOT so that a wider variety of concrete mixtures could be evaluated besides those for bridge decks; this method is expected to evaluate concrete mixtures with maximum aggregate sizes up to 1 inch. Since no concrete mixtures on the existing apparatus have cracked to date, a proposed new scope was made in February 2016 to include investigating a 2 inch versus 3 inch concrete thickness and investigating a smaller maximum aggregate size in order to expedite the cracking age. Additional free shrinkage measurements were also made to verify some of the previous literature findings and to additionally investigate the influence of other issues such as storing environment and specimen size on shrinkage potential.

1.4 Outline of Report

A summary of the current literature describing existing knowledge related to mixture design selection and shrinkage of concrete can be found in section 2.0. This section also covers the details of the apparatus setup and test methodologies performed. In section 3.0 is a summary of the results that were obtained from the mixture designs tested on restrained ring apparatus. Section 4.0 covers results obtained from free drying shrinkage tests on other mixtures and different variables such as storage environment and sample size. Section 5.0 covers conclusions from the study described in this report. Section 6.0 lists final recommendations on the selection of test method that should be implemented to predict restrained shrinkage in concrete at this time.

2.0 RESEARCH METHODS

2.1 Literature Review

2.1.1 Importance of restrained shrinkage test over free shrinkage test

Shrinkage cracking in concrete has been a significant problem in various concrete structures, including bridge decks. ASTM C157, a simple current standard test method to determine the length change of concrete, helps in determining the free shrinkage of a concrete or mortar prism. However, the free shrinkage test can only provide the values of un-restrained drying shrinkage and only magnitudes of the shrinkage occurring after 1 day after drying is initiated and is highly sensitive to the environment that the sample is subjected to. The magnitude of shrinkage from this free shrinkage test are not well-correlated to the predicted bridge deck cracking seen in the field. A current alternative is one of the two available restrained ring tests, providing the age of cracking that might occur due to a degree of restraint (fixed amount based on the steel inner ring). Both free and restrained shrinkage methods are dependent on the mixture and the environment that the sample is stored in.

Apart from the restraint conditions, the circular geometry of the ring test is unique because it eliminates the end effects of concrete samples. While the test goal is to determine the age of cracking, the samples are visually monitored daily or a data acquisition system helps to reduce the frequency of visual monitoring by recording strain values from the steel ring. The concept of using the strain gauges and data acquisition (DAQ) is that the strain in the steel ring is released when the concrete ring develops a macro-crack, and the exact time of the crack can then be determined from the DAQ recording. Strain gauges are installed and carefully undisturbed on the steel rather than within the concrete so that they can be re-usable for future tests.

There are two standard restrained ring tests available in the United States at this time: the AASHTO T334-08 (formerly PP34-99) and the ASTM C1581. These methods consist of different geometries in the concrete samples and in the steel rings, along with correspondingly different aggregate size restrictions. As a result of the differences, the age of cracking is expected to be also different, even if the same mixture was tested in the same environment. Primarily due to aggregate size restrictions of the ASTM method, several DOTs have implemented the AASHTO instead. Yet because of the larger dimensions of the AASHTO ring, testing labs have noticed that many mixtures never crack with this method (Delatte et al. 2007; Ideker et al. 2013). A major issue with using a test apparatus that never produces cracked samples is that it is impossible to determine whether a mixture will perform well in the field. As such, most past researchers have recommended using the ASTM method for bridge decks. The cracking age for mixtures with nominal maximum aggregate sizes that conform to the ASTM standard is expected to be from 2 to 28 days (Hossain and Weiss 2006; Fleurimond 2011; ASTM 2013). The cracking age of the ASTM (or AASHTO) methods does not necessarily correlate to the age of cracking in field mixtures if the curing conditions are not known or accounted for (Delatte et al. 2007).

Both AASHTO and ASTM methods still depend on a constant controlled environment in order to have accurate or repeatable results. This environment is specified to be 70.4 to 76.4 °F (roughly 21 to 25 °C) temperature and 46 to 54% relative humidity. The same data acquisition system can be used for both tests as a means to monitor the strains in the steel ring.

2.1.2 Other Restraint Test Methods

In addition to the AASHTO T334-08 and ASTM C1581 ring shrinkage tests, several other tests have been developed to test the shrinkage of concrete using different restraining test apparatus. These alternative test geometries include a free-end frictional restraint prism, a two-end-restraint with or without friction prism or dogbone, an elliptical ring, and a dual concentric ring test. These methods have been created in research laboratories and have not been adopted as United States standards at this time. Some of these alternative methods are reviewed below.

The dual-ring restrained test has been proposed to ASTM as a future standard at this time. This system includes two steel rings: one on the inside and one on the outside of the concrete ring in order to capture both shrinking and expanding concrete mixtures. It is considered more useful than the current ASTM C1581 particularly for bridge deck applications that might incorporate shrinkage-compensating, internal-cured, or other patching materials besides normal concrete (Schlitter et al. 2010). In order to provide more precision over the control on temperature during the testing, this dual ring method also proposes an insulating box with a temperature coil system on the top of the specimen in the same dual-ring test apparatus (Schlitter et al. 2010).

The free-end frictional restraint test method involves casting a concrete prism against a rigid surface to generate additional friction along the length of the concrete. Under standard environmental conditions, the prism deflects and curls upward from the unrestrained ends. This upward deflection can be measured over time for the ends and along the prism length. Also cracking across the prism length can be noted as time of appearance, distance along length, and width of crack over time. One version suggests a 52 inch (1.3 m) long x 4 inch (100 mm) width x 2 inch (50 mm) thick prism cast onto a steel plate below with sand grit between the steel and new concrete (Poston et al. 1998). Another version of this method suggests a 40 inch (1 m) long x 4 inch (100 mm) wide x 4 inch (100 mm) thick beam cast directly on an existing concrete substrate (Banthia et al. 1996).

Fixed end-restraint tests have also been attempted by researchers. A dogbone style was adapted by RILEM TC119 for testing thermal cracking potential of mass concrete (RILEM 1997). This consists of a 49 inch (1.2 m) long span x 6 inch (150 mm) wide x 6 inch (150 mm) thick specimen. Similar geometries have been performed in different studies by Weiss et al. and by Carslwärd on 39 inches (1 meter) long samples of 1.5 inches (35mm) concrete thickness (Weiss et al. 1998; Carlswärd 2006). The displacement, internal strain, or crack formation is measured over time. The end-caps are made of steel and are attached to the concrete provide the end restraint, which is expected to resemble similar restraint conditions imposed by girders to a concrete bridge deck. For the RILEM method specifically, the concrete sits in an ambient temperature condition for up to four days. After the four days, if the concrete has not cracked, the sample temperature is cooled at a constant rate until cracking occurs. Based on studies related to the RILEM method, it has been understood that concrete that cracks at higher temperatures in this test is prone to early cracking. With end restrained or ring specimens in general, cracking may either occur at one location and become wider with time, or occur at multiple locations if there is internal reinforcement, such as with fiber-reinforced concrete (FRC).

2.2 Factors Affecting Restrained Shrinkage in Labs

2.2.1 Temperature

Prediction of the cracking tendencies in a quasi-brittle material like concrete is difficult due to the sensitivity of concrete towards changing environmental conditions. Also, in order to determine the cracking tendencies associated with different concrete mixture proportions, it is required to have the same environmental conditions and same test geometry. In particular, environmental factors like temperature and relative humidity are considered to be the major contributors of the environmental conditions. A simple prediction of free drying shrinkage is shown in equation 1. An adjustment factor to the shrinkage prediction for ambient temperature effects on drying shrinkage of concrete is shown in equation 2 from the Swedish Concrete Handbook (Carlswärd 2006), which represents that as the temperature increases, the shrinkage would decrease. The net strains that will be measured on the ring shrinkage are expected to follow that of equation 3. There is expected to be some dependence from the heat of hydration at early ages as well. Concrete samples will exhibit internal temperature and moisture gradient, which both change in time, distance to the nearest exposed surface, and magnitude of the ambient conditions. By keeping the ambient conditions constant in the room, geometry constant, and monitoring over time, the shrinkage and cracking will thus only be dependent on the mixture's properties.

2.2.2 Relative Humidity and Curing

Relative humidity is fundamentally the driving environmental factor for drying shrinkage in concrete. While thermal contraction may also contribute or accelerate drying shrinkage, it is the moisture loss that causes internal capillary pressures and strains to develop. The free shrinkage test is meant to capture this drying shrinkage through the net length change; however it does not fully capture any of the internal pressure changes or internal strain reduction that some additives like FRC or lightweight aggregates in concrete can provide.

The theory is that an increase in relative humidity would decrease drying shrinkage, as was proposed with different scaling factors shown in equation 4. Poston et al. studied the influence of relative humidity (from 20, 50 and 90%) on concrete's free drying shrinkage and verified that the highest strains occurred at the lower relative humidity (Poston et al. 1998).

$\varepsilon_{total-Concrete} = \varepsilon_{ultimate} * \gamma_{time} * \gamma_{ambient\ temperature} * \gamma_{RH} * \gamma_{curing}$ where $\varepsilon_{total-Concrete}$ = total (net) strain in concrete ring alone $\varepsilon_{ultimate}$ = maximum strain in concrete after an infinite amount of time γ_{time} = multiplying factor to scale drying shrinkage of the concrete based on age $\gamma_{ambient\ temperature}$ = multiplying factor to scale drying shrinkage of the concrete based on ambient temperature γ_{RH} = multiplying factor to scale drying shrinkage of the concrete based on ambient relative humidity γ_{curing} = multiplying factor to scale drying shrinkage of the concrete based on initial moist curing	(Eqn.1)
$\gamma_{ambient\ temperature} = \frac{293}{T + 293} e^{5000\left(\frac{1}{T+273} - \frac{1}{293}\right)}$ where T= ambient temperature measured in degrees Celsius	(Eqn. 2)
$\varepsilon_{total-Concrete+Steel\ Ring} = \varepsilon_{thermal\ steel} + \varepsilon_{thermal\ concrete} + \varepsilon_{drying\ shrinkage\ concrete} = \mathrm{C}TE_{steel} * \Delta T_{steel} + CTE_{concrete} * \Delta T_{concrete} + \varepsilon_{drying\ shrinkage\ concrete}$ where $\varepsilon_{total-Concrete+Steel\ Ring}$ = total (net) strain in concrete specimen and steel ring $\varepsilon_{thermal\ steel}$ = thermal strain in the steel ring $\varepsilon_{thermal\ concrete}$ = thermal strain in the concrete ring $\varepsilon_{drying\ shrinkage\ concrete}$ = drying shrinkage strain in the concrete ring CTE = coefficient of thermal expansion of that material ΔT = change in temperature in that ring	(Eqn. 3)
$\gamma_{RH} = 1.55 * \left(1 - \left(\frac{RH}{100}\right)^3\right)$ where RH= ambient relative humidity (from 0 to 100)	(Eqn. 4a) from (Carlswärd 2006)
$\gamma_{RH} = \begin{Bmatrix} 1.0 & for\ RH < 40 \\ 1.40 - 0.0102 * RH & for\ 40 \leq RH \leq 80 \\ 3.00 - 0.030 * RH & for\ 80 \leq RH \leq 100 \end{Bmatrix}$	(Eqn. 4b) from (ACI 209 2008)

Curing condition also influences the magnitude of shrinkage. The AASHTO standard calls for curing of 24 hours with wet burlap. Others have reported moist curing the same ring apparatus for anywhere from 0 to 14 days (Delatte et al. 2007; Fleurimond 2011) with un-reported effect on cracking. The lack of initial curing has been reported to increase the magnitude of the total free shrinkage, as is shown in equation 5.

$\gamma_{curing} = \begin{cases} 1.82 & for\ t_{curing} < 3\ days \\ 0.6 + 0.4 * \left(\frac{28}{t_{curing}}\right) & for\ t_{curing} \geq 3\ days \end{cases}$ where t_{curing}= number of days subjected to moist curing	(Eqn. 5a) from (Carlswärd 2006)
$\gamma_{curing} = \begin{cases} 1.2 & for\ t_{curing} = 1\ day \\ 1.1 & for\ t_{curing} = 3\ days \\ 1.0 & for\ t_{curing} = 7\ days \\ 0.93 & for\ t_{curing} = 14\ days \end{cases}$	(Eqn. 5b) from (ACI 209 2008)

2.2.3 Cement Content or Paste Content

Cement content in concrete is a factor used in the ACI 209 guide document for prediction of shrinkage and creep (ACI 209 2008). While this uses the mass of the cement, it is expected that it is the volume of paste (cement + SCMs + water) in the total concrete that actually dominates the magnitude of drying shrinkage of the mixtures. As the overall paste content increases, for the same water-to-cement ratio, the free drying shrinkage was found to increase (Krauss and Rogalla 1996; Carlswärd 2006; Yurdakul et al. 2014; Zhang et al. 2014). Or similarly, for an increase in paste content from 1148 to 1233 pcy, the AASHTO ring shrinkage cracking age was delayed by 8 days (Fleurimond 2011). Thus, mixtures with increased amounts of cementitious materials will have a faster cracking age or wider crack widths. The type of cement used in a mixture was only found to have a slight effect if you use a Type III cement of higher fineness, producing a higher free drying shrinkage than a Type I of equivalent chemistry (Piasta and Sikora 2015).

2.2.4 SCM vs Pure Cement Blends

Use of supplementary cementitious materials (SCM) or mineral admixtures and pozzolans contribute to the cementitious paste content in the mixture and in general are added to reduce permeability in the concrete. It may be expected that all SCMs reduce shrinkage due to the reduced permeability. Yurdakul, et al. studied slag at 20 and 40% replacement of cement, class C and class F fly ashes at 15 and 30% replacement of cement, and ternary blends of cement-slag-ash. The authors found that binary and ternary blends all did better than plain concrete for free drying shrinkage (Yurdakul et al. 2014). The specific type of SCM or amount was not found to be significant on shrinkage reduction. Similarly, Delatte et al. studied the use of class C fly ash using the AASHTO restrained ring test and found these mixtures all took more than 36 days to crack (Delatte et al. 2007).

2.2.5 Water-to-Cementitious Ratio

Although water-to-cement content is not a parameter used in the ACI 209 prediction guide, it is still considered by most researchers to be the most influencing parameter effecting shrinkage in concrete. Water-to-cement or water-to-cementitious (w/cm) ratio does also influence most other concrete properties like strength and permeability which are related to cracking or moisture movement as well. An increase in w/cm ratios in the range of 0.3 to 0.62 have been studied by various researchers and with a constant paste content there is a decrease in free drying shrinkage (Hossain and Weiss 2004; Zhang et al. 2014). Autogenous shrinkage was found to be a higher percent of that total free drying shrinkage at lower w/cm ratios, yet the total shrinkage is still lower at these low w/cm ratios for the same binder content (Zhang et al. 2014). Without holding the paste content constant (such as with a constant cement mass but increased water amount), one might see that for an increased w/cm ratio, the shrinkage also increases (Yurdakul et al. 2014) or the age of cracking drastically decreases (Fleurimond 2011).

2.2.6 Aggregate Size and Blending

Influence of aggregate content and aggregate types on the fresh or hardened properties of concrete was studied by several researchers as well. Opposite to the amount of paste content, as the total volume or mass of aggregates in the concrete mixture increases, then the drying shrinkage decreases (Zhang et al. 2014). A study has found that increasing the fine-to-coarse aggregate blend mass ratio from 0.45 to 0.55 lead to a small two day delay in the age until cracking occurred in the AASHTO ring test (Fleurimond 2011). Also concrete made with a maximum size aggregate of 3/8” (9.5 mm) was found to have earlier cracking and more shrinkage, compared to concrete with a maximum size of ¾” (19 mm) or 1” (25 mm) aggregate (Delatte et al. 2007). Delatte et al. also found gravels had a tendency to crack more than limestone mixtures. Furthermore, they also found that lightweight aggregates delayed the age of cracking on the AASHTO ring test.

2.2.7 Entrained Air Content

The addition of air entrainment in concrete is reported by the ACI 209 as a parameter that increases predicted shrinkage (ACI 209 2008). Research studies have further verified an increase by up to 90 microstrain for air contents for 0.15 to 0.3% by cement mass dosage rates of an air-entraining admixture (Piasta and Sikora 2015) or for 2 to 8% total air content. indicated that the use of air entrainment actually increases shrinkage (Yurdakul et al. 2014).

2.2.8 Restrained Ring Geometry

A study by Hossain and Weiss found that increasing the steel thickness of the inner ring from 0.125 inch to 0.75 inch (3 mm to 19 mm) with a 3” tall (75 mm) concrete ring, the degree of restraint also increased, and the concrete cracked at earlier ages from longer than 14 days to less than 12 days (Hossain and Weiss 2004).

A previous version of the ASTM was based on other research that originally used a top-bottom open ring apparatus (Hossain and Weiss 2004; Turcry et al. 2006), compared to the current circumferential drying apparatus (Shah et al. 1992) of the ASTM C1581 and AASHTO TT334-08. A study found that for the same 3” tall (75 mm) concrete ring apparatus, the top-bottom style produced a much longer age before cracking appeared (Hossain and Weiss 2006).

Among the current standard test methods, the AASHTO T334-08 uses a 3 inch (75mm) concrete ring thickness, while the ASTM C1581 uses a 1.5 inch (38mm) concrete ring thickness. A study on the effect of concrete thickness, found that increasing the thickness of the concrete outer ring from 1.5” (38 mm) all the way up to 6” (150 mm) lead to a delay in the cracking age from 5 to over 14 days (Hossain and Weiss 2006). Delatte et al. also specifically compared 1.5” thick (38 mm) ASTM apparatus to a larger version with a 2.5” thick (63 mm) (Delatte et al. 2007). He found a correlation only applicable to the different ASTM ring sizes and the age of cracking, shown as equation 6. An alternative way to view these specimen geometries is in terms of a surface area-to-volume ratio, where Hossain and Weiss investigated from 0.37 in^{-1} down to 0.11 in^{-1} and Delatte et al. only from 0.37 in^{-1} to 0.23 in^{-1}, both observing a greater cracking age with the reduced surface area-to-volume.

$\frac{R_{OC}}{R_{IC}} = -0.0025 * t_{cracking}^2 + 0.13 * t_{cracking} + 0.3188$ where R_{OC} = outer radius of the concrete ring R_{IC} = inner radius of the concrete ring $t_{cracking}$ = age of cracking (days)	(Eqn. 6) from (Delatte et al. 2007)

2.3 Materials and Methodology

During the time-frame of the entire project, several concrete mixes were designed and cast to better understand the cracking performance of a mix, and to initially gauge the cracking age of what a typical mixture would have using the apparatus. A summary of these mixtures used on the restrained ring apparatus is provided in Section 2.4.1. Additional tests to measure the free shrinkage and split tensile strength of some of the mixtures were also performed in order to help predict the magnitude of shrinkage that could be expected of the mixtures used on the restrained ring test at UDOT. The design parameters investigated for the free shrinkage test include: ambient test environment, paste amount, w/c ratio, aggregate size and blending, air entrainment, and specimen size.

2.3.1 Restrained Ring Test Method

The restrained ring test setup at UDOT conforms to AASHTO T 334-08, which explains that the test method helps in determination of the cracking tendency of restrained concrete specimens. The procedure is known to be comparative and doesn’t intend to determine the time of cracking of concrete in service structures. Variations like aggregate source, gradation, cement and cementitious material type and content, water content and chemical admixtures, can be determined through this test procedure.

The test procedure involves the casting of a 3-inch thick concrete ring around a ½ inch thick, machine smooth, steel ring of 12-inch outer diameter and 6-inch height. The test consists of four strain gauges which were mounted at mid height on the inner surface of the steel ring. As the concrete shrinks with age, steel exerts a restraint force on the concrete ring, generating some strain in the total body of concrete and steel. The strains observed from the inner surface of the steel ring are configured to be collected by the InstruNet data acquisition software every 30 minutes.

According to aforementioned review of previously conducted research, in order to compensate the thicker 3-inch concrete ring specified in the AASHTO method, studies were also conducted on a 2-inch thick concrete ring. All the other dimensions of test setup were maintained unaltered throughout the test process. The idea behind studying a smaller thickness or increased surface area-to-volume ratio of concrete ring is to determine a better method of accelerating the test process.

2.3.2 Materials Studied

The cement used in this study was a Type I/II/V from LaFarge-Holcim Devil's Slide location. A class F fly ash was also used in this study from the Headwaters Navajo plant. The air-entraining admixture (AEA) used in the study was MicroAir from BASF Corporation. Some mixtures used a high-range water reducer (HRWR) which was Glenium 3400 from BASF Corporation.

The fine aggregate used in all mixtures meets ASTM C33 standard and is from Staker-Parson's Beck Street plant. Two different types of coarse aggregates were studied in the process of the research; a limestone that had a maximum aggregate size of 3/4 inch and pea gravel that had a maximum aggregate size as 3/8 inch. Both coarse aggregates were obtained from Staker-Parson's Beck Street plant. As observed in Figure 2.1, the limestone and pea gravel were both gap graded. Some of the mixtures contained a blend of the limestone-pea gravel-fine aggregate at 30%-40%-30% by mass. This blended mixture was also used in the wet-sieve study, where anything over ½” (12mm) was removed after mixing. It is noted here that initially this wet-sieve process was done on a limestone-fine aggregate blend, yet because of the gap grading in the limestone, all that remained was mostly fine grade sizes.

To verify if the test apparatus can indicate when cracking occurs, it is critical that a concrete mixture crack while on the apparatus. While most of the standard mixtures used on the apparatus did not crack, a separate study began to investigate possible other mixtures that might have higher magnitudes of shrinkage. Thus, free drying shrinkage was also monitored for at least 28 days on each restrained ring mixture, as is described in Section 2.4.

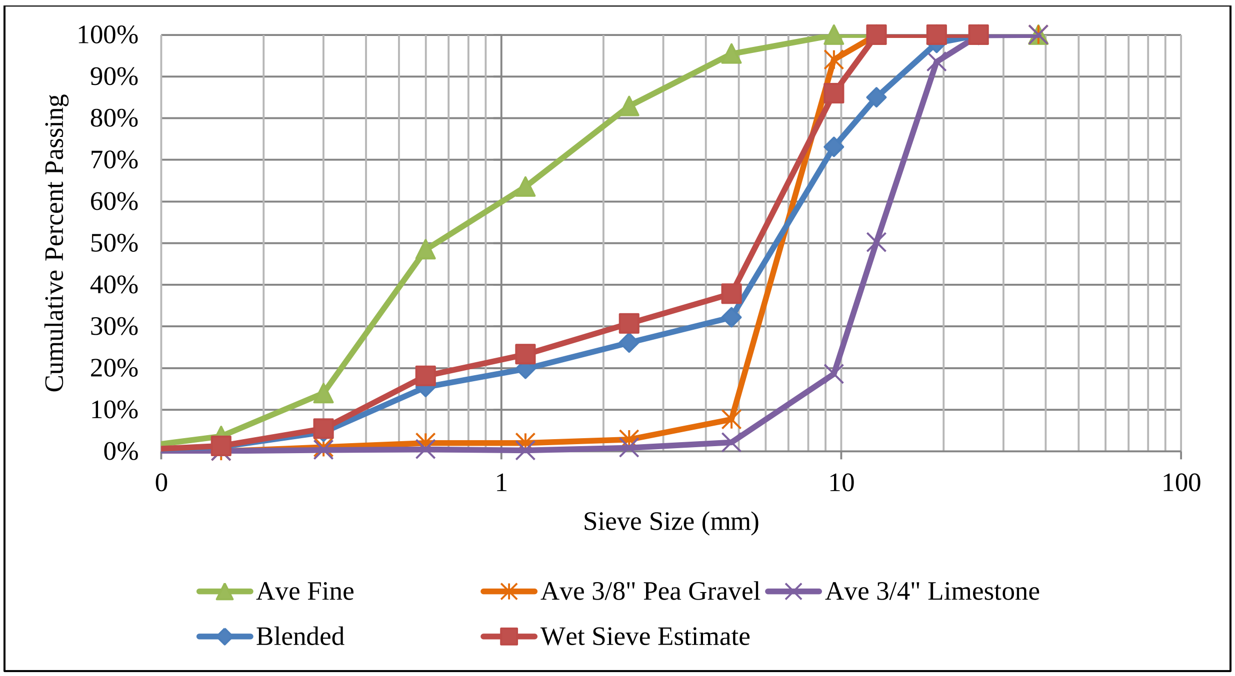

Figure 2.1 Gradation curve for the individual aggregate types and blended aggregates used in the study.

2.3.3 Mixtures for Ring Apparatus

Table 2.1 shows the different concrete mixtures which have been cast and monitored using the restrained ring shrinkage apparatus at the UDOT laboratory. Since each test was run for 28+ days, and since there were only 4 ring setups available, the number of tests shown is small and most tests did not have replicates.

Table 2.1 Concrete Mixtures Tested in Restrained Shrinkage at UDOT

Cast Date	Age Demold (days)	Crack Age (days)	Test Type	Concrete Thickness	w/cm	Vw/Vs	Type II Cement	Fly Ash	Total Cemen -titious	Sand	Coarse Aggregate	Total Aggregate	AEA and/or HRWR
8/12/15	146		Ring	3"	0.38	0.18	8.8%	5.1%	13.9%	32.6%	38.4%	71.0%	Yes
9/9/15	118		Ring	3"	0.38	0.18	8.8%	5.0%	13.8%	32.3%	38.0%	70.3%	Yes
9/28/15		14	Ring	3"	N/A								
10/28/15	69		Ring	3"	0.32	0.26	20.7%	0.0%	20.7%	58.7%	0.0%	58.7%	Yes
1/11/16	63		Ring	2"	0.37	0.16	9.6%	3.2%	12.8%	33.5%	39.7%	73.2%	Yes
1/25/16	11		Ring	3"	N/A								
2/5/16	68		Ring	2"	0.37	0.16	9.6%	3.2%	12.8%	33.5%	39.7%	73.2%	Yes
2/5/16	68		Ring	2"	0.37	0.16	9.6%	3.2%	12.8%	33.5%	39.7%	73.2%	Yes
2/5/16	68		Ring	3"	0.37	0.16	9.6%	3.2%	12.8%	33.5%	39.7%	73.2%	Yes
3/16/16	28		Ring	3"	0.37	0.18	10.6%	2.9%	13.5%	35.9%	35.5%	71.4%	Yes
4/15/16	90		Ring*	2"	0.47	0.24	9.2%	5.3%	14.6%	20.2%	45.8%	66.0%	No
4/15/16	90		Ring	2"	0.47	0.24	9.2%	5.3%	14.6%	20.2%	45.8%	66.0%	No
4/15/16	90		Ring*	3"	0.47	0.24	9.2%	5.3%	14.6%	20.2%	45.8%	66.0%	No
4/15/16	90		Ring	3"	0.44	0.23	9.4%	5.4%	14.8%	20.3%	46.2%	66.5%	No
7/18/16 & 8/15/16		3 to 7 & 8	Ring	2"	0.53	0.68	24.3%	0.0%	24.3%	35.1%	0.0%	35.1%	No
7/18/16 & 8/15/16		21 to 23 & 10 to 14	Ring	3"	0.53	0.68	24.3%	0.0%	24.3%	35.1%	0.0%	35.1%	No

*Wet sieved

2.3.4 Ambient Environment for Ring Test

The environment at UDOT Central Materials Lab room where the restrained rings are stored is controlled through the building facilities. The room's temperature and relative humidity (RH) have been monitored since October 8th, 2015 every 30 minutes within an accuracy of 1 °F and 0.5% RH. Apart from regularly recording the strain gauge readings from the ring specimens, attempts were made to provide a more consistent control of the relative humidity in the UDOT room. A humidifier set to 50% RH was added to the test room in January 2016, but only with constant water supply in Feb 2016.

The room environment did not meet the AASHTO specification even after the humidifier was added. Table 2.2 shows the minimum and maximum temperatures and humidity levels for the time-range that the environment was recorded. It also shows the calculated average daily fluctuation in the same time-ranges. The fluctuation in the temperature did decrease with the addition of the humidifier, as seen in Figure 2.2. Yet also with the addition of the humidifier, the actual room humidity fluctuated more and rarely reached values that met the AASHTO standard. Despite these room environment issues, several restrained ring mixtures were still created while working to develop the DAQ system.

Table 2.2 Minimum and Maximum Temperature and Humidity Levels

	Temperature (F)				**Relative Humidity (%)**			
Time range	Min	Max	Ave	Ave Daily Fluctuation	Min	Max	Ave	Ave Daily Fluctuation
October 7, 2015 – Jan 26, 2016 Initial recording period	55	78	70	6.2	17	57	29	8
Jan 27, 2016 – July 14, 2016 Humidifier with constant water supply	66	77	73	4.2	21	52	36	11

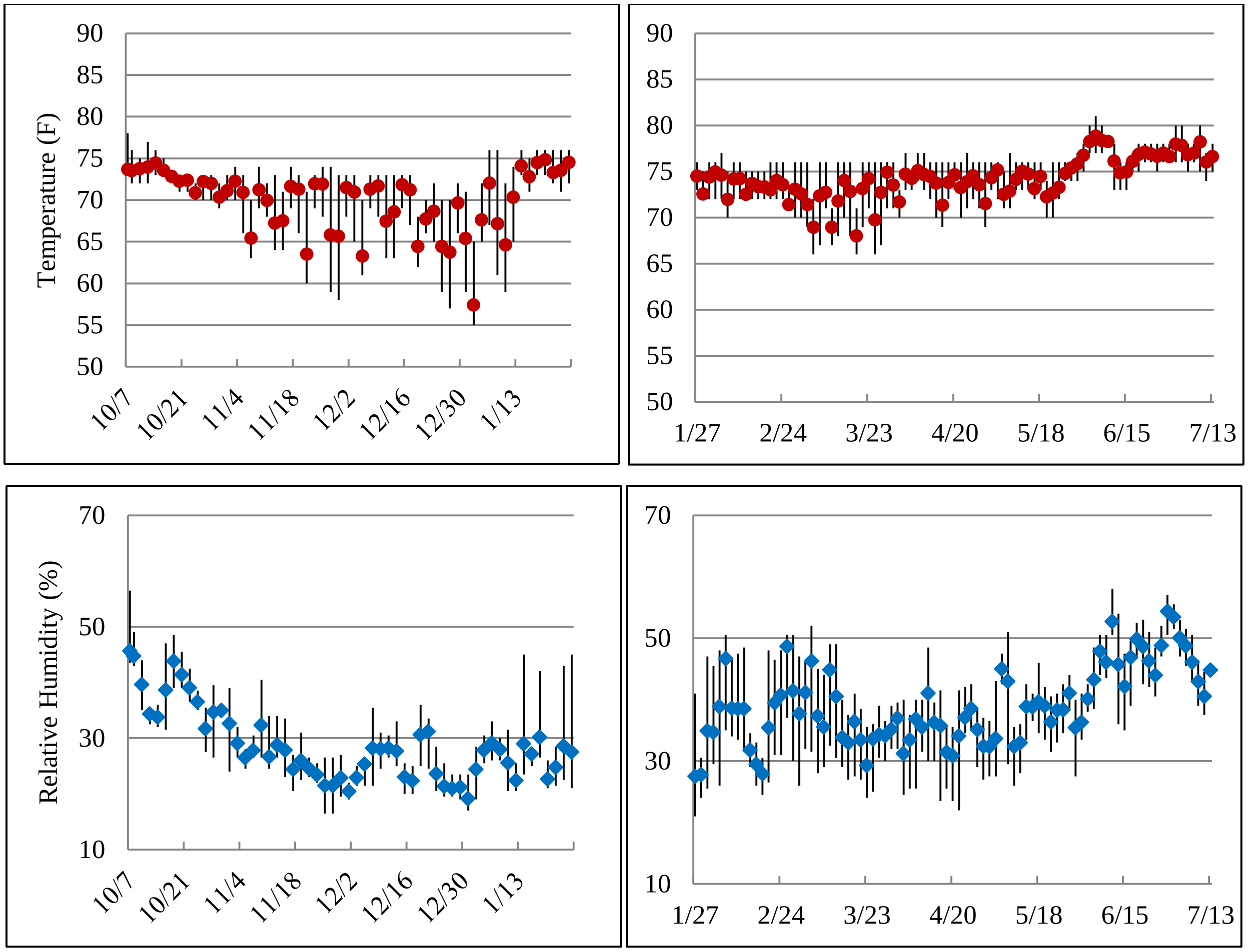

Figure 2.2 Actual daily fluctuations in temperature and humidity. Bars indicate the range of daily min-max while dots indicate the average for day.

2.3.5 Restrained Ring Shrinkage Instrumentation at UDOT

The overall apparatus layout at the UDOT facility is shown in Figure 2.3. The specific wiring of the strain gauges is shown in Figure 2.4. Since the initial setup was completed in August 2016, several iterations were made over the InstruNet data acquisition setup in order to reduce the noise and sensitivity. The supplier of the system, OMEGA, indicates that noise in the data is directly linked to the magnitude of voltage through the power supply. As such, both the internal 3.3V supply from the InstruNet box and an external 12V power supply were compared. An increased voltage will reduce the noise within the system, but will also increase the sensitivity of the strain gauges to the surrounding temperature. When the system was switched to the 3.3V internal supply, small changes in output voltage could not be detected any further and the overall strain values were much more discretized. Although the higher power supply of 12V did show a significant influence from the room temperature, it was still able to pick up small changes that could be associated with the concrete as well. Hence, the test set up was rewired and resumed to an input of the 12V power supply for all the four rings available.

Figure 2.3 Updated layout of testing room at UDOT.

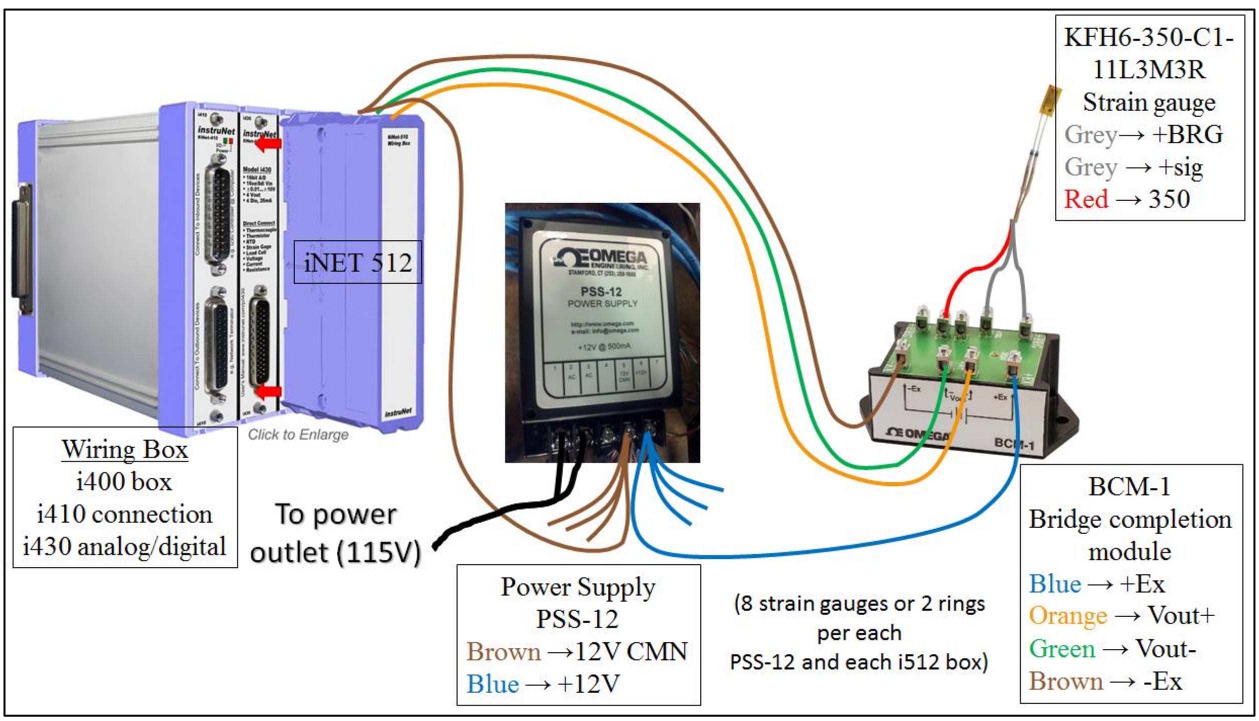

Figure 2.4 Schematic of hardware setup for data acquisition from strain gauges.

The ring shrinkage strain gauge voltage readings can only be temporarily recorded by the software every 30 minutes, and must be downloaded for long-term record manually. Power outages or incorrect settings reading settings have resulted in discontinuities in the measured strain gauge readings.

Most the strain fluctuations shown in the readings are expected to be related to the room's temperature and relative humidity fluctuations. If the magnitude of these fluctuations is high, it may be mistaken as a jump associated with a crack in the concrete. Visual inspection of the concrete rings is the only method to verify whether cracking has occurred. Since some of the data has shown significant strain jumps and no cracking has been found on most samples, it was determined that the temperature and humidity influence be carefully accounted for.

2.3.6 Raw Shrinkage Strain Calculation

As explained in the data acquisition procedure, the raw data obtained from the computer will only display the output voltage (odd numbered channels) and input voltage (even numbered channels). Based on the known values of gauge factor (G_F) and resistance of strain gauges, the total strain values of the quarter bridge connection can be calculated using equation 7.

$\varepsilon_{raw}\,(in\ microstrain) = -4\left(\frac{V_{ratio}}{G_F * (1 + 2V_{ratio})}\right) * 10^6$ $V_{ratio} = \frac{(V_{output,strained} - V_{output,unstrained})}{2 * V_{input,strained} * 1000}$ where $V_{output,strained}$ = odd numbered channel voltage measured throughout reading period (mV) $V_{output,unstrained}$ = odd numbered channel voltage measured from start of recording period (mV) $V_{input,strained}$ = even numbered channel voltage measured throughout reading period (V)	(Eqn. 7)

2.3.7 Compensation for Temperature Variation

The steel ring is also influenced by the temperature of the room, but not the relative humidity. This temperature dependence of the steel alone is considered constant over time and dependent on the steel type's coefficient of thermal expansion.

The type of steel purchased and setup in the Utah DOT's lab is unknown. However, the steel rings while empty of concrete, were monitored for a period of time to determine their temperature dependence.

In order to substantiate the quantitative influence of temperature variations on ring shrinkage apparatus, steel rings were maintained empty for a span of at least 2 days and their strain values were monitored every 30 minutes. Strains in the concrete ring alone were calculated by subtracting out the steel temperature fluctuation, as shown in equation 8.

$\varepsilon_{after\ temp\ compensation}\ (in\ microstrain) = \varepsilon_{raw} - \varepsilon_{temp\ compensation}$ $\varepsilon_{temp\ compensation} = slope * (T) + intercept$ where T = temperature (F) $slope$ = slope based on linear trend line from empty ring, in this case 54.9033 $intercept$ = intercept based on linear trend line from empty ring, in this case -4233.84	(Eqn. 8)

The graphs plotted in Figure 2.5 between temperature variations and calculated strains for an empty steel ring do indicate a correlation. It is important to note here that the magnitude of fluctuation in strain for the same temperature value and for an empty steel ring is significantly high. As such it is hypothesized that the strain gauges and/or DAQ system is likely too sensitive to pick up any small subtle 10-50 microstrain changes expected from the outer concrete ring if the steel ring can fluctuate on its own by over 200 microstrain. Still, the regression equation determined from the unrestrained empty ring is recommended to be used for temperature compensation at this time.

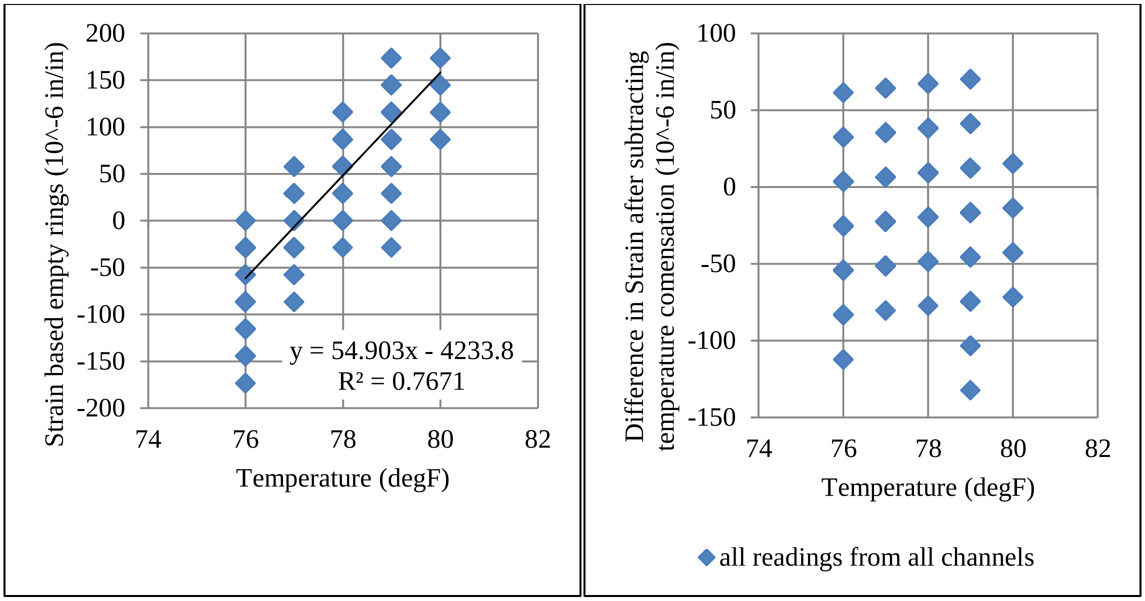

Figure 2.5 Graph showing calculated strains and difference in strains after temperature compensation versus temperature of an empty unrestrained ring.

2.4 Free Drying Shrinkage Test Methods

A modified ASTM C157 standard was used in this project to test various mixture effects on the total free drying shrinkage. The standard has been modified in three ways: alternative specimen sizes were tested, moist curing specified in the standard was not performed, and the air storage environment was specifically investigated for this study.

ASTM C157 defines the test specimen size for mortar to be 1" prisms and for concrete to be either a 4" prism if the aggregate size passes a 2 in. sieve, or a 3" prism if the aggregate passes a 1 in sieve. For this study, only mortar mixtures were investigated. However, besides the standard 1" prism size, 2" and 3" prisms were also created in order to investigate the influence of the surface area per volume on shrinkage.

ASTM C157 suggests all specimens be demolded at 24 hours, and then cured in limewater for 27 additional days, while making the initial reading after 30 minutes of the curing period. It is stated that this moist curing will minimize the variation in length due to temperature. Since the restrained ring specimens are not subjected to the same moist-curing, the free shrinkage specimens for this study were also not moist cured prior to taking a measurement.

The demolding and first reading in this study were done at 12 hours after water was added to the concrete so that an earlier shrinkage value could be recorded.

ASTM C157 also states that for specimens stored in an air environment, the room should be maintained at a relative humidity of 50 ± 4% and a temperature of 23 ± 2ºC. This is the same environmental specification as the restrained ring apparatus methods. Since it was discovered that the room environment may be difficult to maintain, seven different storing conditions were investigated using the ASTM C157 free shrinkage specimens. These storage environments will be presented later in Section 4.1.

Besides the ASTM modifications, additional parameters were also investigated using the free shrinkage specimens. These included various water-to-binder ratios, cement contents, aggregate sizes and types, and the use of air-entraining admixtures. Overall, the sensitivity will be estimated for the ASTM C157 free shrinkage method to differentiate between these various mixtures, environments, and specimen sizes.

2.4.1 Mixtures for Free Shrinkage

Table 2.3 shows the different concrete or mortar mixtures which have been cast and monitored using the free drying shrinkage method. For every location, specimen size, or mixture there were 3-4 replicate specimens made.

2.4.2 Different Storage Environments for Free Shrinkage

The RH and temperature data was gathered for each different storage location as shown in Table 2.4. The resolution of the digital USB logger in UDOT lab (the same room as the ring apparatus was stored in) was 1°F (0.55°C) and 0.5% RH, while all other digital USB loggers had a resolution of 0.5°C and 0.5% RH. The gauge on the humidity chamber displays to the nearest 0.5°C and 0.5% RH, and the dial gauge in the refrigerator had divisions of 2°C and 1% RH (from 10 to 100%). When obtaining RH% data from the refrigerator, and when the dial showed a value below 10%, a rough estimation was used in the analysis of environment condition.

Table 2.3 Mixture Volumetric Proportions for Free Drying Shrinkage Specimens

Cast Date	w/cm	Vw/Vs	Type II Cement	Fly Ash	Total Cemen-titious	Sand	Coarse Agg	Total Agg	AEA and/or HRWR
2/1/16	0.37	0.16	9.6%	3.2%	12.8%	33.5%	39.7%	73.2%	Yes
2/29/16	0.29	0.49	36.3%		36.3%	30.6%		30.6%	No
2/29/16	0.39	0.66	32.6%		32.6%	27.5%		27.5%	No
2/29/16	0.49	0.83	29.6%		29.6%	24.9%		24.9%	No
2/29/16	0.54	0.92	28.2%		28.2%	23.8%		23.8%	No
3/7/16	0.37	0.16	9.6%	3.2%	12.8%	34.1%	39.2%	73.3%	Yes
3/26/16	0.45	0.26	14.5%		14.5%	30.0%	35.1%	65.1%	Yes
3/29/16	0.28	0.33	28.5%		28.5%	46.6%		46.6%	No
3/29/16	0.33	0.42	28.4%		28.4%	42.0%		42.0%	No
3/29/16	0.38	0.52	28.3%		28.3%	37.7%		37.7%	No
3/29/16	0.43	0.63	28.2%		28.2%	33.3%		33.3%	No
3/29/16	0.49	0.75	28.0%		28.0%	29.0%		29.0%	No
3/29/16	0.54	0.90	27.9%		27.9%	24.7%		24.7%	No
3/30/16	0.28	0.33	28.5%		28.5%	46.6%		46.6%	No
3/30/16	0.33	0.42	28.4%		28.4%	42.0%		42.0%	No
3/30/16	0.38	0.52	28.3%		28.3%	37.7%		37.7%	No
3/30/16	0.43	0.63	28.2%		28.2%	33.3%		33.3%	No
3/30/16	0.49	0.75	28.0%		28.0%	29.0%		29.0%	No
3/30/16	0.54	0.90	27.9%		27.9%	24.7%		24.7%	No
4/2/16	0.26	0.13	10.1%	5.1%	15.2%	30.9%	42.7%	73.6%	Yes
4/5/16	0.47	0.42	19.8%		19.8%	23.4%	27.4%	50.8%	Yes
4/14/16	0.44	0.23	9.3%	5.4%	14.7%	20.4%	46.3%	66.7%	No
8/1/16	0.55	0.7	24.2%		24.2%	34.0%		34.0%	No

Table 2.4 RH and Temperature Monitoring Information for Different Locations

Location	Expected Relative Humidity	Expected Temperature	Monitoring Method	Duration between Readings (min)
Refrigerator	10%	10°C	Dial Gauge	Specific dates
Humidity Chamber	50%	23°C	Digital Gauge	Specific dates
Fume Hood	Fluctuating <50%	25°C	USB Logger	10
Room 110A	Fluctuating <50%	25°C	USB Logger	10
Storage Room 130C	Fluctuating ~50%	25°C	USB Logger	10
UDOT	~50%	25°C	USB Logger	30
Fog Room 130D	90%	25°C	USB Logger	10

The maximum, minimum, average temperature and RH data for each location through all the monitoring days is shown in Figure 2.6 and listed in Table 2.5. The readings verified that the refrigerator is extremely colder and lower in humidity. The highest humidity was in the fog room. The daily fluctuations of temperature and humidity for each location were calculated and are listed in Table 2.6. The humidity chamber was verified to maintain a constant temperature and humidity expected for the ASTM C157 specification. The fog room (130D) also had a stable humidity and temperature environment.

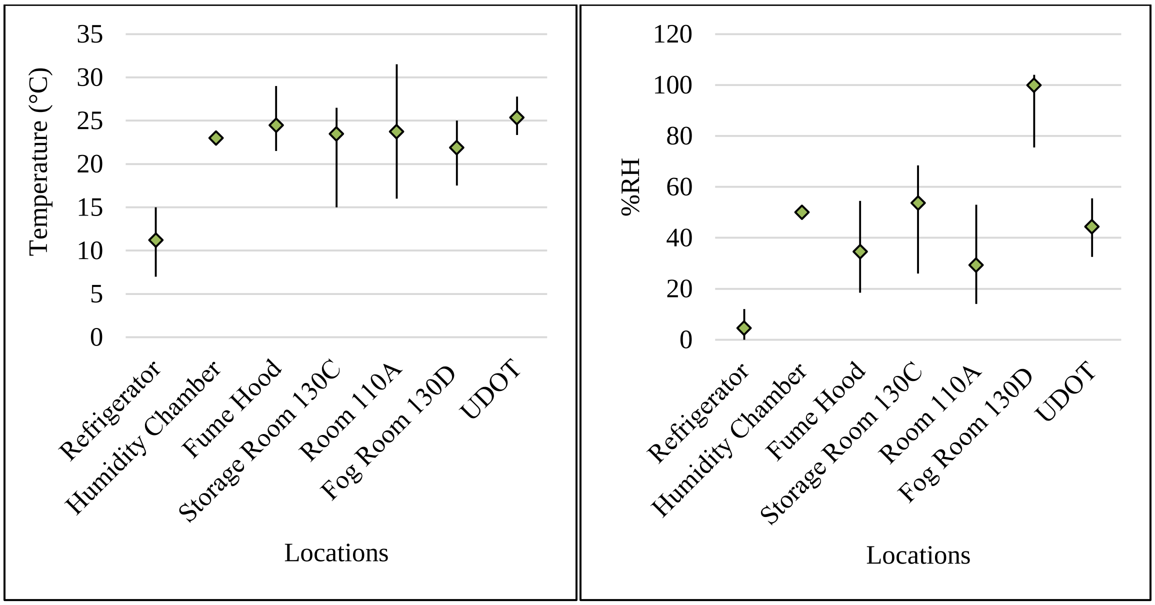

Figure 2.6 Storage room conditions a) relative humidity and b) temperature distributions recorded for May to July 2016. Bars indicate the overall min-max while dots indicate the average.

Table 2.5 RH and Temperature Data for Different Locations

	RH (%)			**Temperature (°C)**		
Location	Minimum	Maximum	Average	Minimum	Maximum	Average
Refrigerator	0.0	12.0	4.5	7.0	15.0	11.2
Humidity Chamber	50.0	50.0	50.0	23.0	23.0	23.0
Fume Hood	18.5	54.5	34.6	21.5	29.0	24.5
Room 110A	14.0	53.0	29.4	16.0	31.5	23.7
Storage Room 130C	26.0	68.5	53.7	15.0	26.5	23.5
UDOT	32.5	55.5	44.3	23.3	27.8	25.4
Fog Room 130D	75.5	104.0	99.9	17.5	25.0	21.9

Table 2.6 Temperature and Humidity Daily Fluctuation for Different Locations

	RH Fluctuation (%)			Temperature Fluctuation (°C)		
Location	Minimum	Maximum	Average	Minimum	Maximum	Average
Refrigerator	3.0	5.0	4.5	3.0	6.0	4.0
Humidity Chamber	0.0	0.0	0.0	0.0	0.0	0.0
Fume Hood	7.0	24.0	14.2	1.5	7.0	3.5
Room 110A	6.0	22.0	14.1	1.5	6.5	3.7
Storage Room 130C	3.0	30.0	9.2	0.0	5.5	1.1
UDOT	2.0	14.0	5.7	0.6	2.8	1.1
Fog Room 130D	0.5	21.5	3.7	0.0	2.0	1.0

3.0 SAMPLE RESULTS ON RESTRAINED RING APPARATUS

Restrained ring shrinkage tests conducted at the UDOT facility, a free shrinkage ASTM C157 test conducted either at UDOT facility or University of Utah Concrete Lab, and a split tensile cylinder ASTM C496 test conducted at University of Utah Concrete Lab were all adopted in testing the concrete samples at both UDOT and University of Utah laboratories. The specifics of the test are described below.

3.1 AASHTO Standard (3”) Versus 2” Modified Version

Figure 3.1 shows a plot of cracking age observed with visual inspection. Each specimen size had four replicates and the properties of the mixtures are shown in Table 2.1. The surface area-to-volume ratios were 0.29in^{-1} and 0.20 in^{-1} for the 2” and 3” rings respectively. It was observed that a ring with 3” concrete thickness took anywhere from 1.4 to 7.7 times longer to crack than the ring with a 2” concrete thickness. This is more variable but has a similar trend to what Hossain and Weiss found in 2006 where they determined an increase in thickness or a decrease in surface area-to-volume from 0.37 in^{-1} to 0.11 in^{-1} increased the cracking age in total by a factor of 2.8 times.

The specific strain data for these specimens can be found in the Appendix. When the specimen cracks, the strain gauges should record a sudden release of strain. However, there is no apparent trend change in the measured strain at the age of cracking and the cracking was detected visually rather than through the recorded strain. This may again be due to the high fluctuation readings of the DAQ strain gauge system for any given moment that the sample is recording.

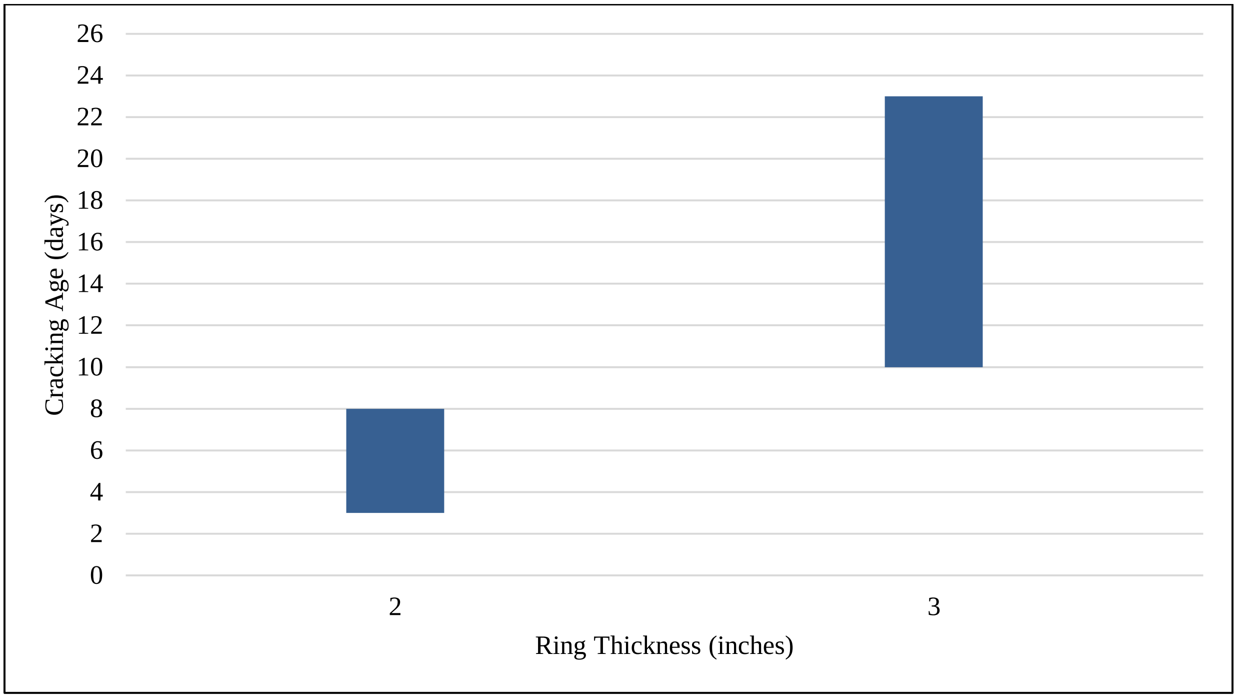

Figure 3.1 Minimum and maximum cracking age for different ring thicknesses given the same mortar mixture tested in the AASHTO apparatus.

3.2 Other AASHTO (3") Ring Results and Discussion

All of the concrete rings did not show any signs of cracking; even for extended observation times of 28-146 days (see Table 2.1). This lack of cracking is a common problem reported with the AASHTO method. From the test specimens in this report, it was verified that mortar mixtures without coarse aggregates and with high paste contents did observe cracking. The first mortar ring to ever crack in this study had a cracking age of 14 days. However, no information was recorded at that time on the mix design of that mortar mixture, as it was a random proportioning mix batched for testing the output of the strain gauges. Since the mixture properties were not known, the mixture could not be replicated.

No concrete samples made to date have cracked on the restrained ring apparatus at the UDOT facility. The brief samples to date investigating the influence of a thinner 2" concrete ring or the wet-sieving method to reduce maximum aggregate size of the concrete placed in the ring apparatus are inconclusive at this time. Again no samples have cracked to date with any mixtures.

Specimens made with the same mix design must be placed in identical environments for the drying shrinkage results to be comparable. This is an issue when trying to correlate the results of the restrained shrinkage test performed in a lab to a bridge deck. The deck is subjected to varying environmental effects and it is difficult to predict what the environment will be. Thus, even if a prediction can be made for the cracking age of a certain mixture in the lab, the cracking age when the specimen (bridge deck) is in a different environment will be different.

The environment (temperature and relative humidity) of the testing room must be monitored and kept relatively constant. Thus, the number of rings that can be casted and monitored simultaneously is limited to the available area and environment. The UDOT environment was too variable with fluctuations beyond the specified standard limits.

Although one can detect cracking visually, continuous data logging of the strains in the rings is preferred as to be able to monitor any strain changes over time and not just the rough age of cracking. The strain gauge system is designed to serve as a backup for predicting the actual age of cracking within a 30 min time-frame. Steel temperature strains and concrete shrinkage strains should be monitored using high quality strain gauges installed by a person with sufficient experience to avoid any measurement errors caused by improperly installed gauges. If poor quality gauges or DAQ system are used, one can expect that there may be significant noise in the strain values, which can mask over any subtle changes from the actual ring cracking. The recorded voltage from the strain gauges can be used to calculate total strain. A separate temperature and humidity effect correlation is needed and was attempted in this study, in order to subtract out the effects of the environment in order to determine the remaining drying strains exhibited by the concrete.

The existing test apparatus that is built according to the AASHTO method may be too large and too robust for assessing whether specific changes in mixture proportions will induce drying shrinkage cracking. Furthermore, the ring test requires a large physical storage space to house the rings. Each ring can take up to 3 square feet of area. The steel ring must be custom made and chosen to have a low thermal expansion to minimize temperature strains.

4.0 SAMPLE RESULTS FOR FREE DRYING SHRINKAGE

4.1 Effect of Environmental Climate of the Room

The free drying shrinkage of 3” prisms at different locations is shown below in Figure 4.1. The specimens stored in a humidity chamber were considered as the control mix following ASTM C157. The shrinkage of those specimens stored in the other six locations was compared. The shrinkage was lowest for those samples stored in the fog room as can be expected since this has the highest humidity. All other storage environments may provide slightly different shrinkage magnitudes, but are not as uniquely different as the fog room.

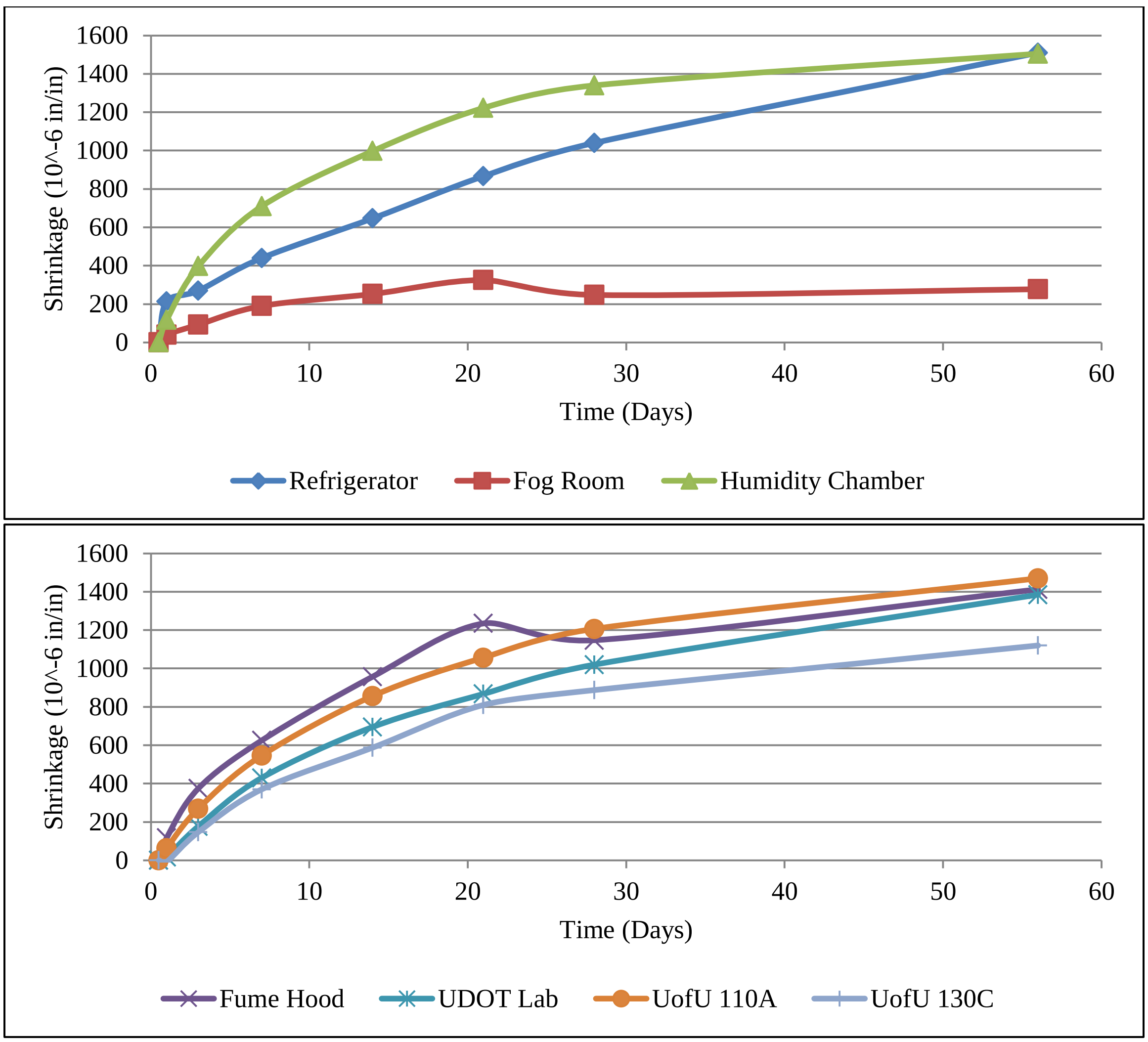

Figure 4.1 Average shrinkage of mortar in different locations for 3” prisms.

4.2 Effect of Paste Content and W/CM Ratio

As discussed in Section 2.2.3, the volume of paste dominates the magnitude of drying shrinkage. As the overall paste content increases for the same water-to-cement ratio, the free drying shrinkage increased among the samples shown in Figure 4.2.

A similar trend would be expected in restrained drying shrinkage tests. The ring apparatus mixtures (Table 2.1) cast with cement contents of 21% or less did not show cracking. Yet those with a higher cement content of 24% did observe cracking, verifying that an increase in paste content causes an increase in shrinkage for the ring test as well as the free shrinkage test

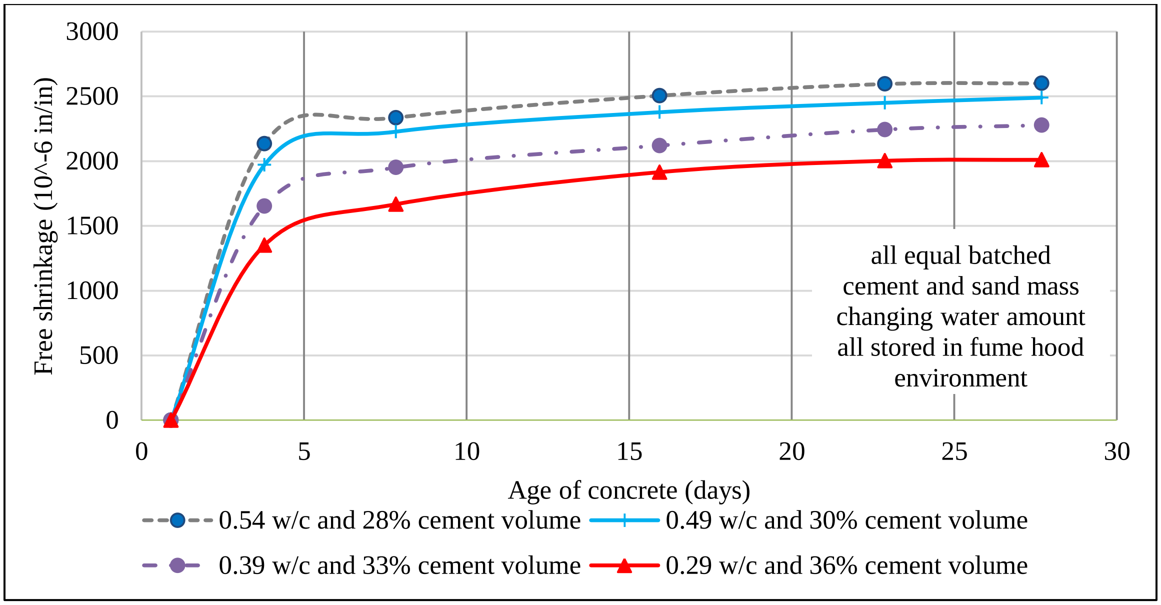

Figure 4.2 Average free shrinkage for mortar mixtures with coupled different w/cm ratios and paste volume fractions due to increased water amount to constant cement-aggregate batch weights.

An increase in water-to-cement ratio by either decreasing the cement content or increasing the water content has an opposite effect of actually decreasing shrinkage. Hossain and Weiss (2004) and Zhang et al. (2014) confirmed that increasing the w/cm by increasing the water content and keeping the cement content constant leads to a decrease in free drying shrinkage. Again, this similar trend was found among the free shrinkage samples shown in Figure 4.3. It is expected a similar trend would be seen among restrained drying shrinkage samples.

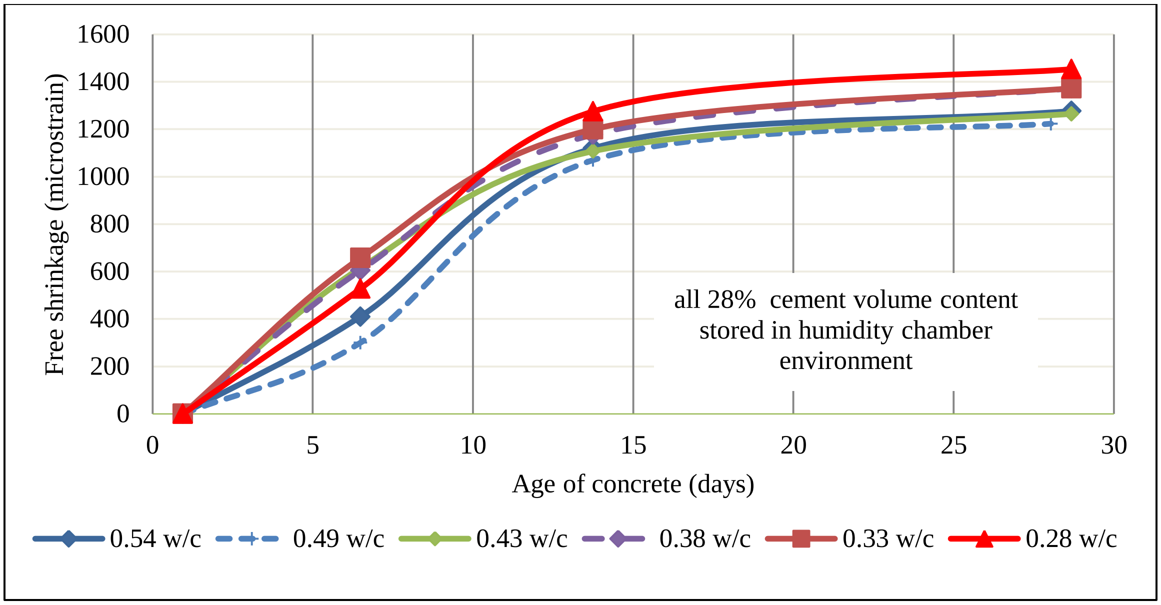

Figure 4.3 Average free shrinkage of mortar mixtures with same cement volume, but varying w/cm ratio.

4.3 Effect of Aggregate

Two different coarse aggregates were investigated. The limestone aggregates with a larger maximum aggregate size produced much lower strains than the pea gravel aggregates, as shown in Figure 4.4 compared to Figure 4.5. These different aggregate mixtures were stored in different environments, but were expected to have similar environmental effects based on the previous findings (Section 4.1) for lab environments.

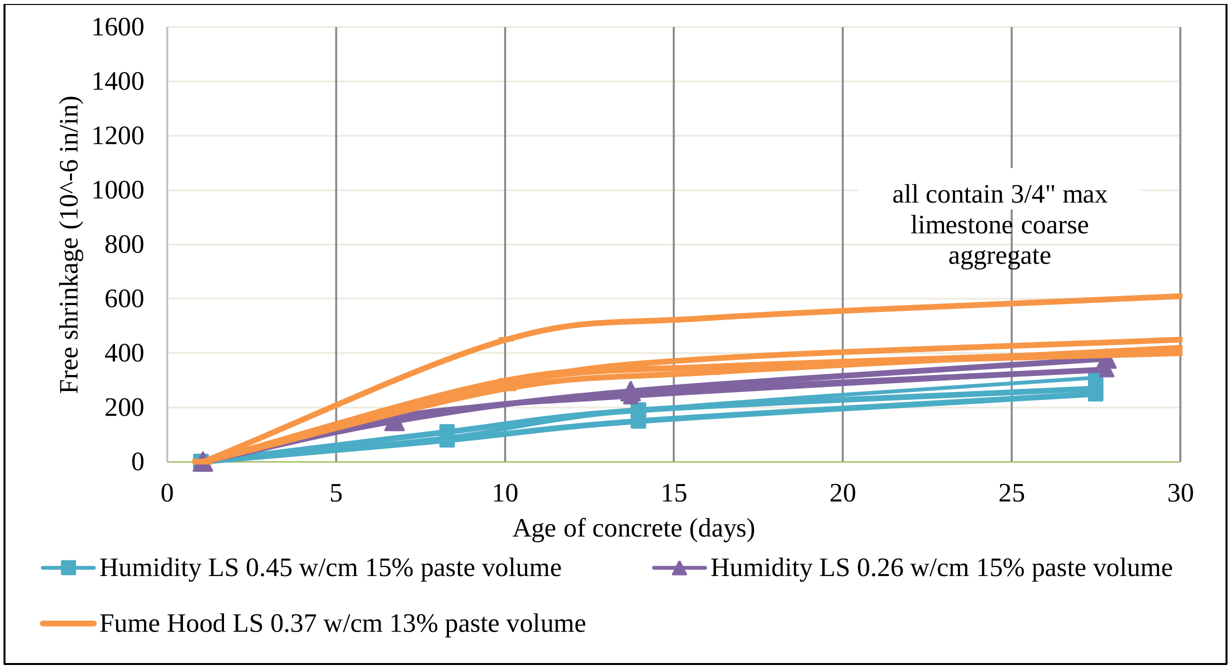

Figure 4.4 Free shrinkage of concrete with 3/4" limestone with 13 to 15% paste volume fraction, and either stored in a fume hood or humidity chamber.

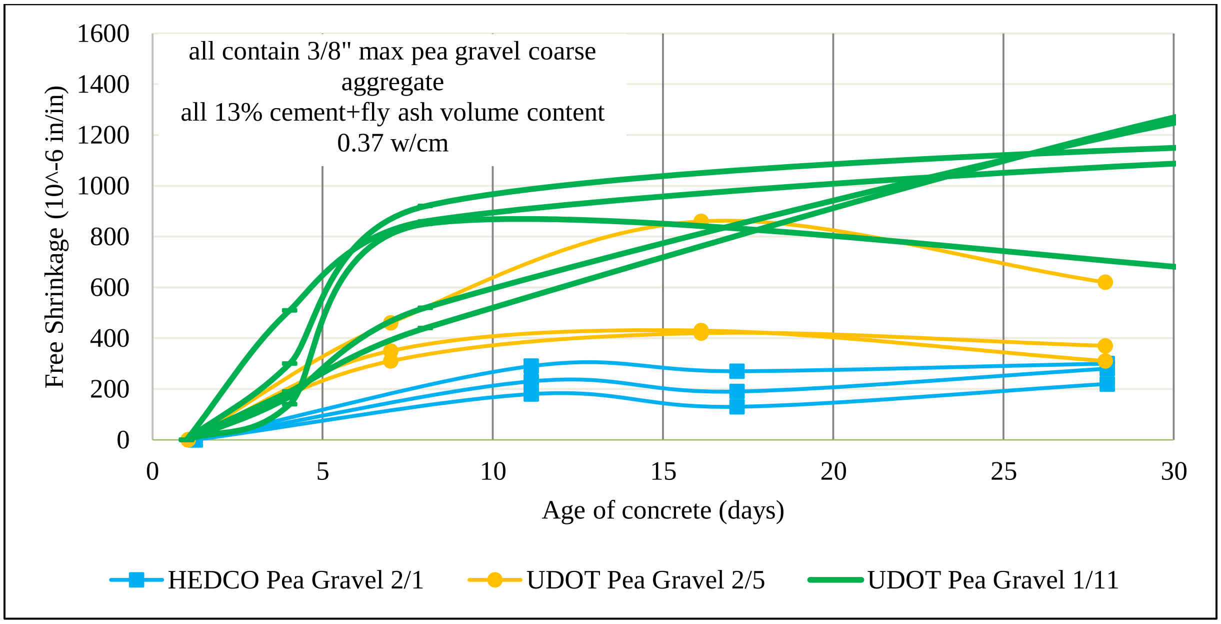

Figure 4.5 Free shrinkage of concrete with 3/8" pea gravel and either stored in the open lab at HEDCO or at UDOT.

4.3.1 Shrinkage with Wet-Sieved Aggregates

In order to confirm the ASTM specification of required maximum size of the coarse aggregate with respect to the thickness of the concrete member, a wet-sieve method was adopted in order to eliminate any higher size of aggregate than ½ inch. As part of this procedure, concrete was mixed as per the planned volumetric ratios of constituents, and then sieved in a plastic state, to eliminate the aggregate larger than ½ inch. This procedure helped maintain the volume of the paste almost constant, while eliminating the larger aggregates. Figure 4.6 compares the free shrinkage of wet-sieved concrete with original mixture concrete.

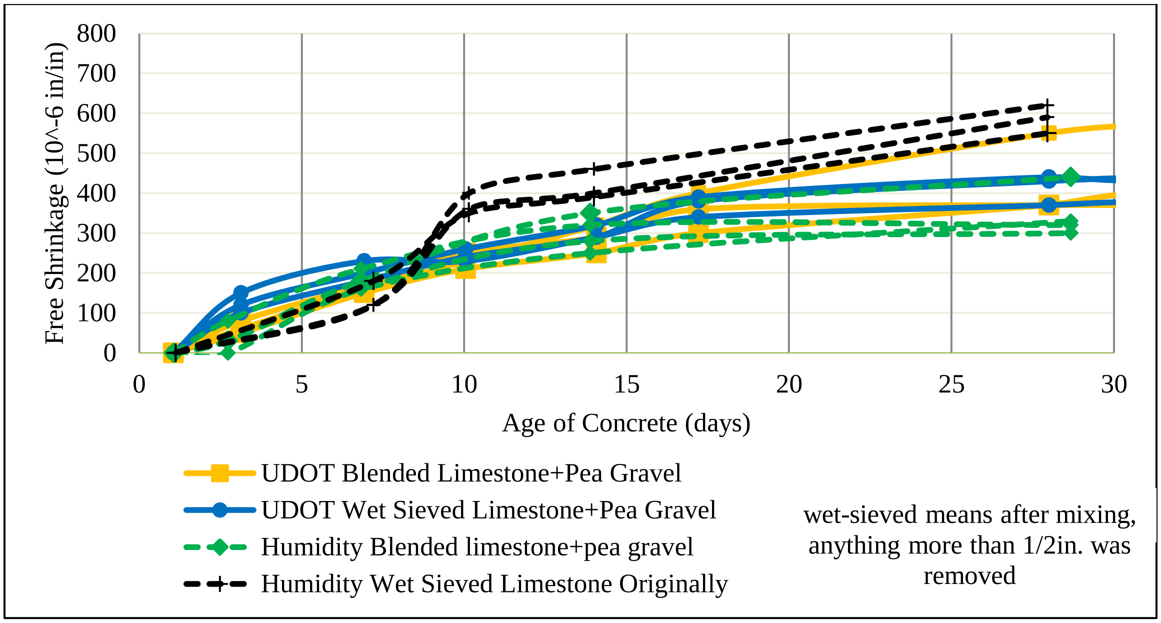

Figure 4.6 Free shrinkage of concrete with original mixture vs wet-sieved. One mixture made with only limestone coarse aggregate, while all others mixed with limestone and pea gravel blend. Stored in either UDOT's open air environment or in the 50% Humidity Chamber.

4.4 Effect of Air-Entrainment

Table 4.1 shows the average (of at least three replicates) free shrinkage of twelve mortar mixtures with approximately equal total cement paste volume of 28%. Each mixture with a specified w/cm was batched with and without air-entraining admixture. Figure 4.7 shows a plot of the free shrinkage over time.

A statistical p-value was calculated on the mean difference between the mean free shrinkage between air-entrained and non-air-entrained mixtures. The null hypothesis is that there is no significant statistical difference between the two means. A p-value of less than 0.05 suggests that there is a statistical difference between the two mixtures. As presented in Table 7, for all w/cm ratios, there p-values indicate that there is likely no significant difference between the free shrinkage of mixtures with and without AEA.

Table 4.1 Average and Statistics on 28 Day Free Shrinkage Containing AEA

w/cm ratio	Air-Entrainment	No AEA	Mean Difference between AEA and non-AEA	P-Value between AEA and non-AEA
0.538	1293	1277	16.63	0.659
0.486	1247	1223	23.4	0.350
0.434	1350	1265	85	0.146
0.382	1360	1373	-12.5	0.839
0.330	1410	1373	-37.5	0.152
0.278	1470	1453	16.67	0.677

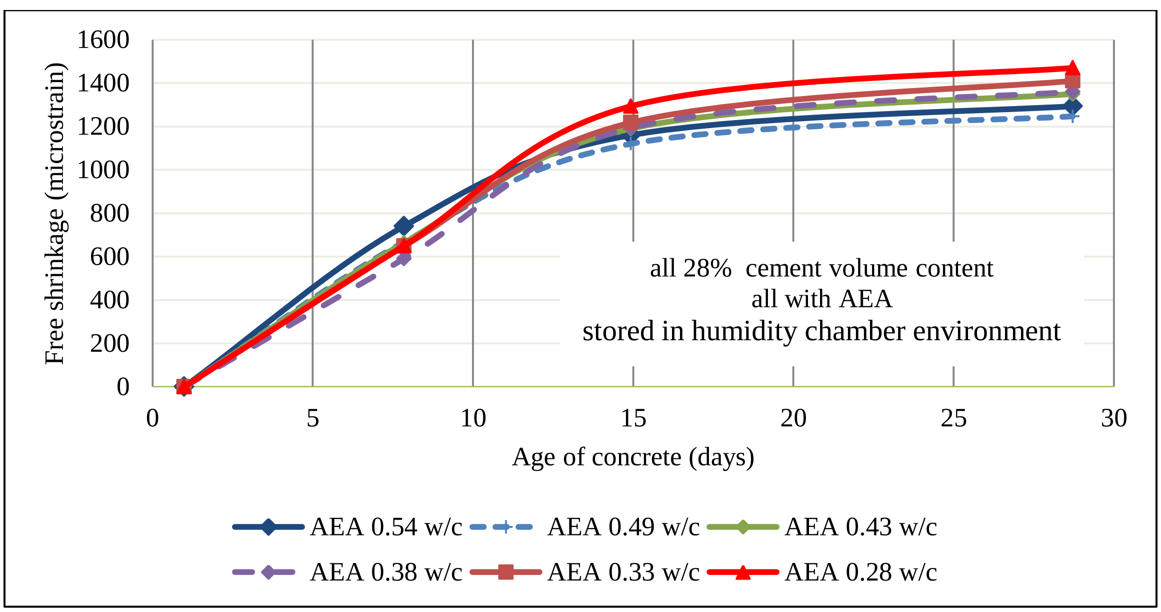

Figure 4.7 Average free shrinkage for mortar mixtures with air-entraining admixture. Different w/cm ratios are shown. All measured in a 50% humidity chamber storage condition.

4.5 Effect of Specimen Size

As discussed in Sections 2.2.8 and 3.1, the shrinkage of concrete is expected to increase as the thickness of the specimen decreases. The surface area-to-volume ratios investigated were 1.51, 2.18 and 4.18 for the 3”, 2” and 1” prisms respectively. As can be seen in Figure 4.8, the specimen sizes have some influence on free shrinkage with the shrinkage decreasing as the size of the specimen increases, just as expected. It is then recommended to decrease the thickness, or an increase in surface area-to-volume ratio of the concrete rings in a restrained shrinkage test to accelerate the cracking process, again as seen with the 2” versus the 3” ring thickness.

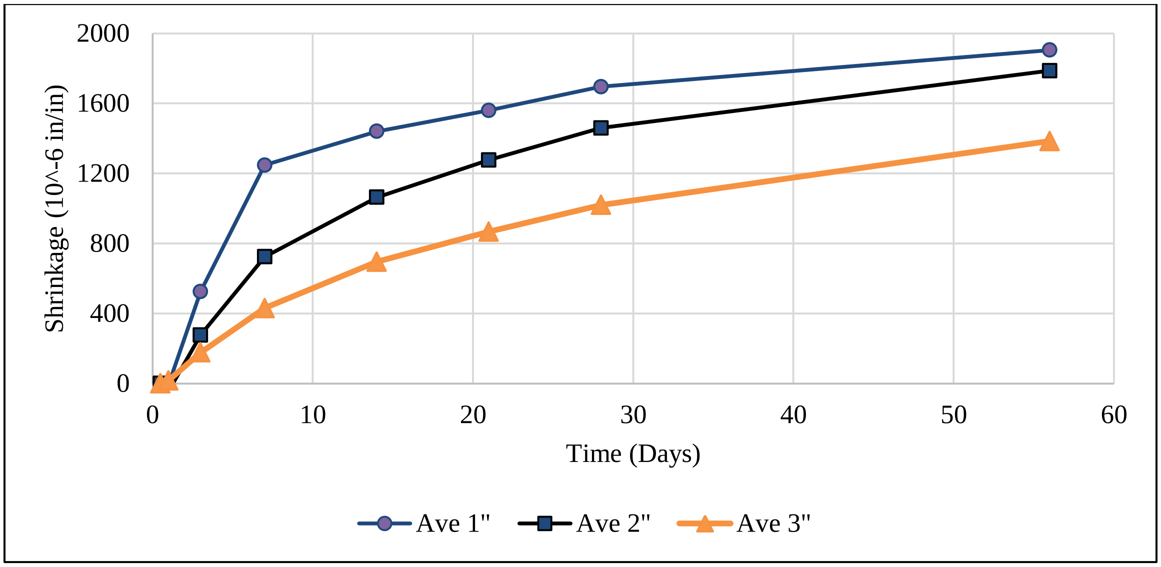

Figure 4.8 Average shrinkage of mortar for different sample sizes in the UDOT lab.

5.0 CONCLUSIONS

A free shrinkage test is not typically used to describe field performance because it does not represent the constrained condition of concrete in a bridge deck. However, this research found that the ASTM C157 free shrinkage method is more favorable than the AASHTO T334-08 ring shrinkage test. The lack of a definitive cracking age or a high variability in cracking age among mortar samples, plus the over-sensitivity of the strain gauges, make the AASHTO restrained ring procedure difficult to implement. The ring shrinkage test can also be very time consuming and often there is no conclusive result if the specimen does not crack.

Both free and restrained shrinkage tests depend on the surrounding environment. The UDOT facility room control on ambient temperature and humidity was too variable for the current AASHTO standard. This should be improved upon for future restrained shrinkage samples.

The free shrinkage test method did provide some insight into how two different mixtures perform relative to each other. Preliminary tests verified that the most dominant factor on shrinkage was the cement volume content. Other factors like w/cm ratio (for constant cement volume), aggregate size or type, specimen size (or surface area-to-volume ratio), and storage environment were also found to have an influence on the magnitude of free drying shrinkage.

A correlation between the age of cracking from the restrained ring test, or free shrinkage measurements to the field bridge deck performance is still needed. This also depends on detailed visual inspection of bridge decks that includes age of cracking and whether it is shrinkage crack patterns versus other distress-caused cracks.

6.0 TEST METHOD SELECTION RECOMMENDATIONS

Several observations were made during the setup of the AASHTO T334-08 ring apparatus that must be taken into account for anyone planning to similarly use this method.

1- Testing Considerations
   a) The steel ring must be custom made and chosen to have a low coefficient of thermal expansion to minimize temperature strains. Invar type steel is the ideal option.
   b) High quality strain gauges are preferred. The gauges should be installed by a person with experience as to avoid any measurement errors caused by improperly installed gauges.
   c) Continuous data logging is preferred as to be able to monitor the changes over time. The data acquisition hardware and software should be carefully chosen based on accuracy and ease of use.
   d) Each ring test specimen takes up to 3 square feet of area and thus sufficient area should be provided for all test specimens. The standard allows for the movement of

the specimen after assembly. However, care should be taken while moving the specimen as to avoid disturbing the sample or wiring attached.

e) The rings should be placed in an environment with a tightly controlled temperature 73 +/- 3 °F and relative humidity 50% +/- 4%.

f) Additional ring setups could also provide for more test mixtures or replicates of each mixture to be tested simultaneously rather than waiting 28-90 days between each sample.

2- Monitoring considerations

a) Temperature and humidity of the environment should be monitored and controlled because extreme fluctuations can cause the sample to crack due to environmental effects rather than mixture effects.

b) In addition to electronic strain monitoring, the ring samples must be visually inspected for verifying the age of cracking.

The high dependability on the surrounding environment and the over-sensitivity of the strain gauges make this AASHTO T334-08 procedure unfavorable in comparison to the ASTM C157 free shrinkage method. The free shrinkage has its own challenges, including similar climate constraints, and the size and curing must be specified for consistency between measurements.

This study has focused mainly on building the apparatus and attempting to ensure the AASHTO T334-08 procedure can be appropriately used to evaluate performance of bridge deck mixtures. High variability and a lack of conclusive results were found in the AASHTO procedure. Thus, it is recommended that UDOT should remain using the ASTM C157 method until an appropriate and consistent restrained shrinkage test procedure is developed.

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APPENDIX A: STRAIN DATA FOR MORTAR MIXTURES ON THE RESTRAINED RING

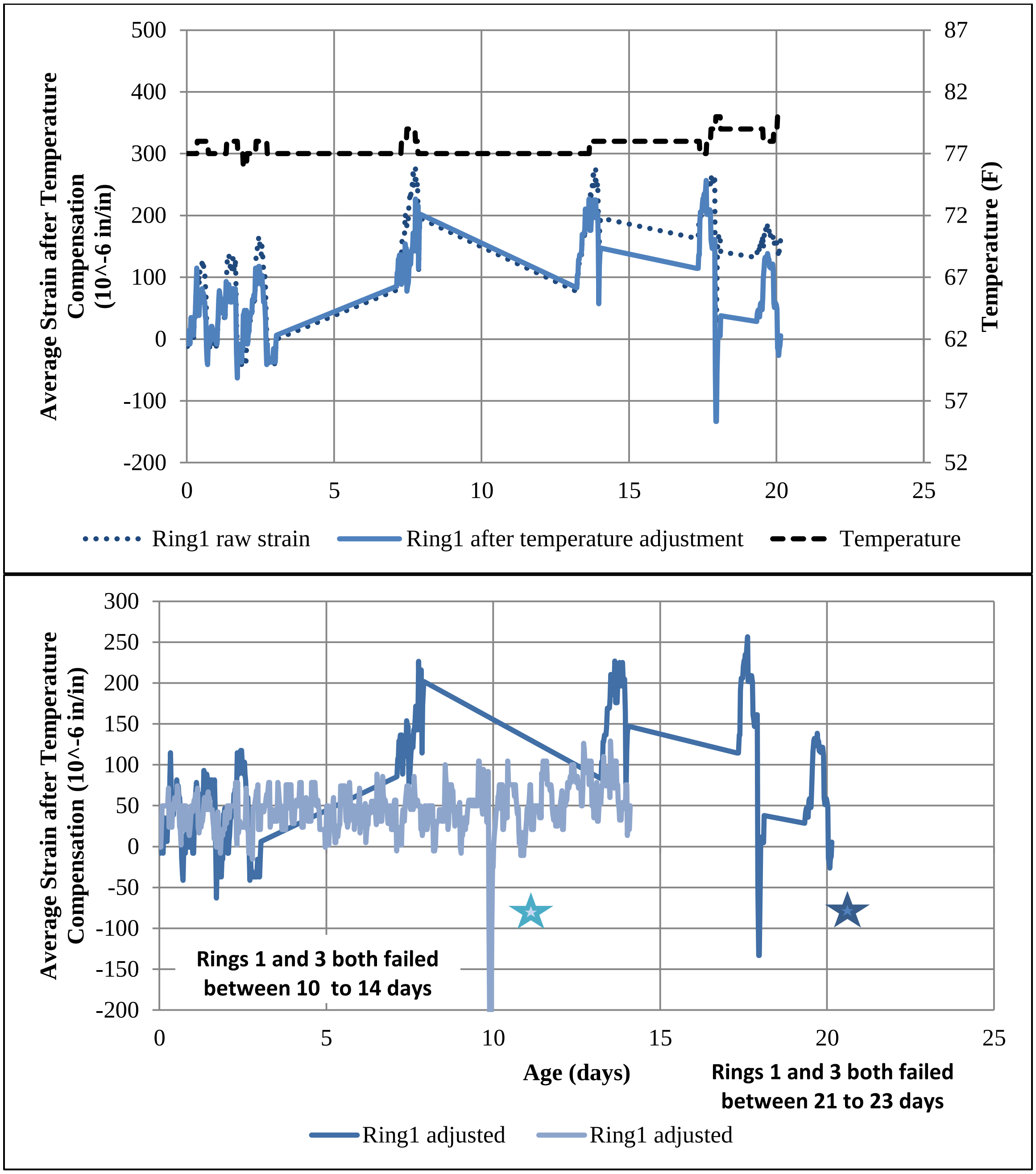

Figure A.1 Raw and adjusted strains for Ring 1 (3" thick) and adjusted strains for two replicates of the same Ring 1 mixture.

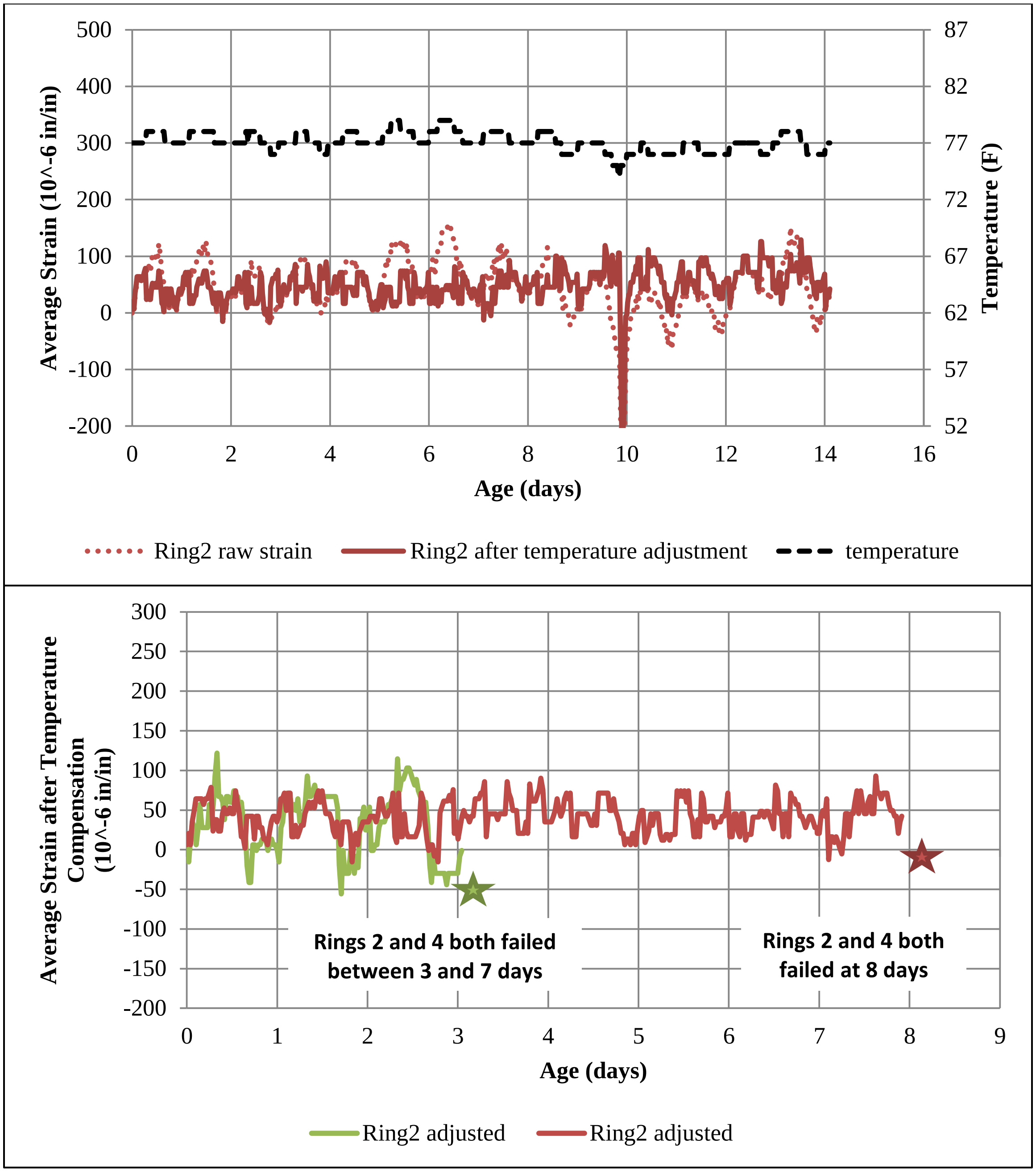

Figure A.2 Raw and adjusted strains for Ring 2 (2” thick) and adjusted strains for two replicates of the same Ring 2 mixture.