RESEARCH

Keeping Utah Moving

Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

Report No. UT-19.07

ASTM C-157 STANDARD AUDIT FOR THIRD-PARTY SHRINKAGE TESTING LABORATORIES TO IMPROVE THE RELIABILITY OF RESULTS FOR CONCRETE MIXES

Prepared For:

Utah Department of Transportation
Research and Innovation Division

Submitted By:

University of Utah
Department of Civil and Environmental Engineering

Authored By:

Avinash Rishi
Pedro Romero, Ph.D., P.E.

Final Report
April 2019

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data (except for shrinkage measurements of concrete specimens tested by third party laboratories), analysis, conclusions, and recommendations presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation or the U.S. Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind and assumes no liability therefore.

ACKNOWLEDGEMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research, and the following individuals for their help on the research:

- Bryan Lee (UDOT)
- Scott Strader (UDOT)
- Scott Morse (Dura-Crete)
- Dustin Wagstaff (Dura-Crete)
- Mark Bryant (UofU)
- Amanda Bordelon (UVU)

TECHNICAL REPORT ABSTRACT

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UT-19.07	N/A	N/A

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
ASTM C-157 STANDARD AUDIT FOR THIRD-PARTY SHRINKAGE TESTING LABORATORIES TO IMPROVE THE RELIABILITY OF RESULTS FOR CONCRETE MIXES	5. Report Date: April 2019 6. Performing Organization Code: N/A
7. Author(s): Avinash Rishi, Pedro Romero	8. Performing Organization Report No.: N/A
9. Performing Organization Name and Address: University of Utah Department of Civil and Environmental Engineering 110 Central Campus Dr. Salt Lake City, UT 84112	10. Work Unit No.: 5H08014H 11. Contract or Grant No.: 18-8992
12. Sponsoring Agency Name and Address: Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410	13. Type of Report & Period Covered: Final Report, April 2018 to January 2019 14. Sponsoring Agency Code: UT16.108

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

Shrinkage of concrete is one of the reasons of concrete cracking in bridge decks. To minimize such cracks, concrete mixes with minimal shrinkage potential is used. This shrinkage potential was evaluated by third party shrinkage testing laboratories as per ASTM C-157 standard. However, significantly different results were obtained from different laboratories for the same mixes. For this reason, it was necessary to do an ASTM C-157 standard audit for third party laboratories to improve the reliability of such results. The Utah Department of Transportation (UDOT) was interested in selecting a shrinkage acceptance value for concrete mixes, and therefore sponsored this research project to better understand the variability and reliability of the results.

For this purpose, different laboratories were visited to collect information on existing practices followed and capability of the laboratories to perform such tests. Three laboratories were selected to perform the ASTM C-157 free shrinkage test on concrete specimens. The duration of curing period was kept to 7 days, including the period in molds, due to time constraint. The procedures followed by the labs and the method to obtain and maintain the recommended temperature and relative humidity were noted. In the process, different methods of initial curing and to maintain the recommended temperature and relative humidity were observed. The date at which shrinkage measurements were taken also differed. It was observed that the labs were able to maintain the temperature within the recommended limits for most duration of the test. However, the relative humidity was lower than recommended limits. Moreover, the shrinkage of concrete specimens at 28 days was significantly different.

To conclude, the methods used by the laboratories to maintain the required relative humidity were not satisfactory. Different methods of initial curing and to maintain the temperature and relative humidity have significant effect on the shrinkage measurements. To improve the reliability of the results, such differences should be eliminated, and one common accepted method should be followed by all laboratories. This would allow the use of single laboratory, multiple operator precision values recommended in ASTM C-157 standard as a reliability check.

17. Key Words	18. Distribution Statement	23. Registrant's Seal
Shrinkage, concrete, ASTM C-157	Not restricted. Available through: UDOT Research & Innov. Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research	N/A

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	35	N/A

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

UNIT CONVERSION FACTORS

Units used in this report and not conforming to the UDOT standard unit of measurement (U.S. Customary system) are given below with their U.S. Customary equivalents.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

EXECUTIVE SUMMARY

Shrinkage of concrete is one of the reasons for concrete cracking in bridge decks. To minimize such cracks, concrete mixes with minimal shrinkage potential are used. This shrinkage potential was evaluated by third-party shrinkage testing laboratories as per the ASTM C-157 standard. However, significantly different results were obtained from different laboratories for the same mixes. For this reason, it was necessary to do an ASTM C-157 standard audit for third-party laboratories to improve the reliability of such results. The Utah Department of Transportation (UDOT) was interested in selecting a shrinkage acceptance value for concrete mixes, and therefore sponsored this research project to better understand the variability and reliability of the results.

For this purpose, different laboratories were visited to collect information on existing practices followed and capability of the laboratories to perform such tests. Three laboratories were selected to perform the ASTM C-157 free shrinkage test on concrete specimens. The duration of the curing period was kept to 7 days, including the period in molds, due to time constraints. The procedures followed by the labs and the method to obtain and maintain the recommended temperature and relative humidity were noted. In the process, different methods of initial curing to maintain the recommended temperature and relative humidity were observed. The date at which shrinkage measurements were taken also differed. It was observed that the labs were able to maintain the temperature within the recommended limits for most of the duration of the test. However, the relative humidity was lower than recommended limits. Moreover, the shrinkage of concrete specimens at 28 days was significantly different.

To conclude, the methods used by the laboratories to maintain the required relative humidity were not satisfactory. Different methods of initial curing to maintain the temperature and relative humidity have significant effect on the shrinkage measurements. To improve the reliability of the results, such differences should be eliminated, and one common accepted method should be followed by all laboratories. This would allow the use of single laboratory, multiple-operator precision values as recommended in the ASTM C-157 standard as a reliability check.

1.0 INTRODUCTION

1.1 Background

Concrete cracking in bridge decks is a major problem. Shrinkage of concrete is one of the reasons for concrete cracking. Cracks are aesthetically undesirable, reduce strength of concrete, allow water and other harmful chemicals to enter concrete and cause corrosion of reinforcements, and cause freezing and thawing problems. Shrinkage of concrete can be reduced by designing mixes for minimal shrinkage. Various state Departments of Transportation (DOTs) have a maximum acceptance value of free shrinkage for selecting concrete mixes to be used. The Utah Department of Transportation (UDOT) was interested in selecting an acceptance value for concrete mixes, and therefore sponsored this research project to better understand the variability and reliability of the results.

The value of free shrinkage was evaluated by third-party testing laboratories as per ASTM C-157. However, significantly different results were obtained from different laboratories for the same mixes. Variations were seen in the methods to cure specimens during the first 24 hours of curing, including methods to achieve the required temperature and relative humidity and storage conditions of specimens. The effect of these on shrinkage measurements is unknown. Hence, it was necessary to have an ASTM C-157 standard audit for third-party shrinkage testing laboratories.

1.2 Problem Statement

As discussed, various state Departments of Transportation (DOTs) depend on third-party laboratories for ASTM C-157 test results. However, the results obtained are significantly different. Results from one laboratory may indicate that the concrete mixture is suitable for use while the results from other laboratories may indicate otherwise. Hence, it is important to do an ASTM C-157 standard audit to establish the capability of the selected laboratories to perform such tests. This would help to provide recommendations to improve its reliability.

1.3 Objectives and Scope of Work

The main objective of the research is to do an ASTM C-157 standard audit for third-party shrinkage testing laboratories and provide recommendations to improve the reliability of the results.

Several shrinkage testing laboratory companies in the Salt Lake City area were visited to collect information on capability and existing practices to perform the ASTM C-157 test. A concrete mixture was selected to perform the modified ASTM C-157 free shrinkage test due to time constraints. The concrete mixture was subjected to standard temperature condition of 73 ±3 °F (23 ± 2 °C) and relative humidity of 50±4% to evaluate the variability associated with the modified ASTM C-157 test method. The results were compared with the precision values specified in the standard. At the end, recommendations were made to improve the reliability of the test results.

1.4 Outline of the report

In section 2, a summary of existing knowledge related to shrinkage can be found. This section includes a brief description on microstructure of concrete, different types of concrete shrinkage, free and restrained shrinkage test method and factors affecting free shrinkage of concrete. Section 3 covers the test method. It includes ASTM C-157 recommended conditions and procedures. It also includes existing test conditions and procedures. Information on molding of specimens, specimen size, curing procedures and air storage can also be found in section 3. Section 4 shows the shrinkage results obtained along with temperature and relative humidity measured over the test period. Analysis on shrinkage results can be found in section 5. Section 6 covers the conclusion and recommendations from the observed results.

2.0 LITERATURE REVIEW

2.1 Microstructure of concrete

The microstructure of concrete is responsible for most of its properties. The microstructure of concrete consists of three components: hydrated cement paste, aggregates, and interfacial transition zone (ITZ) between cement paste and aggregates.

The aggregate phase is responsible for unit weight, elastic modulus and dimensional stability of concrete. These properties of concrete depend on physical characteristics such as volume, size, pore distribution, shape, and texture of aggregates. The aggregate phase is the strongest phase and has little influence on the strength.

The hydrated cement paste consists of three principal components: solids, air voids, and water. Solids are of four types: calcium silicate hydrate (C-S-H), calcium hydroxide, calcium sulfoaluminates, and un-hydrated cement particles. Calcium silicate hydrate (C-S-H) makes up 50 – 60 % of the volume of solids and to a large extent decides the properties of hydrated cement paste. Calcium hydroxide and calcium sulfoaluminates comprise about 20 – 25 % and 15 – 20 % of the volume of solids, respectively, and have little influence on the properties of concrete. Un-hydrated cement particles may be present depending on the time since mixing with water and size of anhydrous cement particle. Voids are of three types: interlayer space in C-S-H, capillary voids, and air voids. Interlayer space in C-S-H is too small to influence strength and permeability of the hydrated cement paste. Capillary voids are space not occupied by solid particles in the hydrated cement paste. Capillary voids are smaller than air voids and are irregular in shape whereas air voids are spherical in shape and are more detrimental to the strength of concrete. Water is of four types: capillary water, adsorbed water, interlayer water, and chemically-bound water. Capillary water is free from influence of attractive forces exerted by solids. They are further divided into two types: free water (removal of which does not cause any volume change) and water held by capillary tension (removal of which causes volume change). Adsorbed water is physically adsorbed onto the surface of solids under the influence of attractive forces exerted by solids. Interlayer water is held by hydrogen bonding in the interlayer space in C-S-H. Chemically combined water is used during the hydration reaction and forms part of the various hydration products.

The cement particles in fresh concrete, which are suspended in the mix water, cannot pack together as efficiently when they are in the close vicinity of a much larger solid object, such an aggregate particle. The result is a narrow region around the aggregate particles with fewer cement particles, and thus more water. This is called the interfacial transition zone, often abbreviated as ITZ. ITZ is a 10 – 50 μm thick region formed around coarse aggregates. It is more porous compared to bulk cement paste or mortar. ITZ is the weakest phase of the microstructure of concrete and governs the mechanical behavior such as tensile strength, inelastic behavior of concrete, etc.

2.2 Types of Shrinkage

Concrete undergoes volume change due to movement of water to and from concrete to achieve moisture equilibrium with the surrounding environment. Shrinkage is concrete contraction that happens due to loss of water and it shows logarithmic growth with time. Common types of shrinkage occurring in concrete are described herein.

Thermal shrinkage is caused by temperature difference between concrete and the surrounding environment. Materials expand when heated and contract when cooled. When temperature of the surrounding environment is less than the concrete temperature, concrete will shrink.

Plastic shrinkage is caused by the loss of water from the surface of fresh concrete by evaporation. Plastic shrinkage is restrained by non-shrinking inner concrete layers causing differential strains between outer and inner concrete layers, leading to surface cracks.

Autogenous shrinkage (also known as chemical shrinkage) is caused by water loss due to hydration of cement. It does not include water lost to the surrounding environment.

Drying shrinkage is caused by water lost from the hardened concrete to the surrounding environment. Among different types of shrinkage, drying shrinkage results in the largest change in volume.

Carbonation shrinkage is caused by reaction between hardened cement paste and carbon dioxide. A consequence of carbonation is loss of water.

2.3 Restrained Shrinkage Test vs. Free Shrinkage Test

At present, there are two types of test methods on concrete shrinkage: Restrained shrinkage test and free shrinkage test. Both methods are used for selecting concrete mixes that are less likely to crack.

The restrained shrinkage test gives a cracking age of concrete when restrained. It is used to compare different concrete mixtures. As the name implies, a mixture with a later cracking age would crack late on field when compared to a mixture with an earlier cracking age. There are two existing standards: AASHTO T 334-08 and ASTM C-581 on restrained shrinkage test. These methods consist of different concrete and steel ring geometries, along with different aggregate size restrictions. AASHTO T 334-08 is preferred to ASTM C 1581 due to aggregate size restrictions of ASTM C 1581.

Allahham et al. (2016) concluded that ASTM C-157 free shrinkage test is easier to implement than AASHTO T 334-08. In their research most mixtures tested in the ring shrinkage test did not crack. It is difficult to predict the on-field performance of such non-cracking mixtures. Influence of the surrounding environment, high variability in cracking age and high dependence of result on strain gauges were other problems reported with the restrained shrinkage method.

The free shrinkage test provides unrestrained shrinkage of concrete to compare different concrete mixtures. Currently, ASTM C-157 is used to measure free shrinkage of concrete. Although free shrinkage tests do not give a cracking age, there is a correlation between free shrinkage value and cracking tendency of concrete.

Radlińska and Weiss (2012) proposed a stochastic approach to develop a performance related specification by relating free shrinkage of concrete specimens to the time of cracking and probability of cracking. It is important to note that the samples were tested for a period ranging from 275-365 days. Monte Carlo simulations were used to obtain a probabilistic assessment of concrete cracking performance. An example of performance-related specification for shrinkage obtained from AASHTO-PP84 (2017) is shown in Figure 1. Four performance grades of 1,2,3 and 4 are assigned based on cracking probability ranges of 100% – 50%, 50% – 20%, 20% – 5% and 5% – 0% respectively. Grade 4 is assigned to concrete mixtures with minimal probability of cracking. As can be seen from Figure 1, the higher the free shrinkage, the greater is the probability of cracking. For example, a mixture with a free shrinkage value of 600 μ has approximately 4% probability of cracking compared to concrete mixture with free shrinkage value of 900 μ, which has approximately 70% probability of cracking. The former mixture is assigned a higher grade (grade 4) while the latter is assigned a lower grade (grade 1); i.e. the former mixture will perform better on-field than the latter. Generally, an acceptable value of probability of cracking is selected, and then the corresponding free shrinkage value is selected as the maximum limiting value of free shrinkage. For example, if an acceptable probability of cracking is 5%, free shrinkage value of concrete as per ASTM C-157 shall be limited to 625 µ.

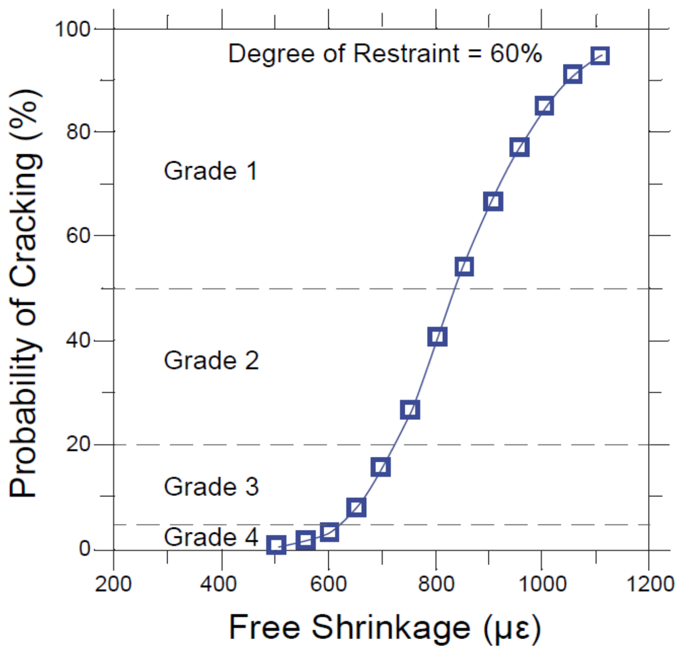


Figure 1 Results from Monte Carlo simulations to develop performance-related specifications (AASHTO PP 84-17).

2.4 Factors affecting shrinkage of concrete

Several researches have been conducted on factors affecting the shrinkage of concrete. Most factors are often interrelated. This section summarizes the influence of various factors on shrinkage of concrete.

2.4.1 Effect of w/cm ratio, paste volume and aggregate volume

Loss of water is the cause of shrinkage of concrete. The majority of water is lost from cement paste. In general, the higher the water-to-cement (w/cm) ratio, the larger is the shrinkage (Neville and Brooks 2003). Several researchers have studied the influence of w/cm ratio ranging from 0.26 to 0.5. It was observed that decreasing w/cm ratio from 0.35 to 0.25 decreased the shrinkage strain of concrete for a constant paste volume (Piasta and Zarzycki 2017). Autogenous shrinkage is higher at lower w/cm ratios and decreased with increase in w/cm ratio. However, total shrinkage is still low at lower w/cm ratio when compared to shrinkage at high w/cm ratio for constant paste volume (Zhang et al. 2003). There is a direct proportionality between shrinkage of concrete and paste volume for a constant w/cm ratio. With w/cm ratio constant, shrinkage of concrete increases with increase in cement content and water content as it increases paste volume (Piasta and Zarzycki (2017), Pickett (1956), Benoît Bissonnette et al. (1999)).

Moreover, paste volume and aggregate volume are inversely related. A decrease in paste volume is obtained by increasing the aggregate volume while keeping w/cm ratio the same. Decrease in paste volume (i.e. increase in aggregate volume) increases the amount of water adsorbed onto the surface of aggregates. As a result, evaporable water content of the cement pastes decreases. This decreases the porosity of bulk cement paste and interfacial transition zone (ITZ) leading to improved tightness (Piasta and Zarzycki 2017). Also, aggregates shrink to a very little extent, providing a restraining effect to shrinkage (Neville and Brooks 2003).

2.4.2 Effect of cement and aggregate properties

The magnitude of shrinkage is also influenced by cement and aggregate properties. Fine cement particles hydrate quickly and form a finer pore structure than coarse cement particles. Coarse cement particles, that do not hydrate fully, provide restraint to shrinkage like aggregates (Neville and Brooks 2003). Bennett and Loat (1970) studied ordinary Portland cement with three grades of fineness: 2770 cm^2/g, 4900 cm^2/g and 7420 cm^2/g. The shrinkage increased with cement fineness with shrinkage values of 520 μ, 680 μ and 690 μ reported for cement fineness of 2770 cm^2/g, 4900 cm^2/g, and 7420 cm^2/g respectively. The rate of shrinkage development is higher for finer cement particles; however, the effect on ultimate shrinkage for a given w/cm ratio is limited.

The most important property of aggregate influencing shrinkage is modulus of elasticity. The degree of restraint against deformation provided by concrete depends on the modulus of elasticity of aggregate (Mehta and Monteiro 2006). In general, concrete made with aggregates having a high modulus of elasticity shrinks less. As coarse aggregate forms about 60-80 % of total concrete volume, it is expected that the only properties of coarse aggregate; i.e. coarse aggregate shrinkage strain, specific surface area of aggregates, water absorption and pore structure of coarse aggregate should influence shrinkage. Zhang et al. (2013) studied the influence of these aggregate material characteristics on drying shrinkage of mortar and concrete. The type of fine aggregate studied had little influence on drying shrinkage. On the contrary, the type of coarse aggregate studied had significant influence on drying shrinkage of concrete. It was observed that concrete made with aggregates having lower shrinkage strain and smaller specific surface area had a lower shrinkage strain. They explained decrease in disjoining pressure and shrinkage strain of coarse aggregates with decrease in specific surface area as the cause of lower shrinkage. Another property of aggregate which influences shrinkage of concrete is water absorption. Aggregates with high-absorption capacity require more water to obtain desired workability. The increased water content increases shrinkage. Other properties such as gradation, maximum size, shape and texture of aggregate influences shrinkage indirectly through their effect on paste volume/aggregate volume (Mehta and Monteiro 2006).

2.4.3 Effect of shape and size of the specimen

Another parameter that affects the shrinkage of concrete is the specimen size and shape. Thickness of specimen determines the rate at which water is lost from the interior of concrete to the atmosphere and thus the rate of drying shrinkage. In practice, only the outer part of concrete undergoes shrinkage and its shrinkage is restrained by inner non-shrinking concrete (Neville and Brooks 2003). A parameter, surface area to volume ratio, is used to characterize the influence of size and shape of the specimen on shrinkage. Li (2016) investigated shrinkage of 1”, 2” and 3” prism mortars having surface area to volume ratios of 4.18, 2.18 and 1.51 respectively. He found the shrinkage of specimen to be inversely proportional to surface area to volume ratio. The shape of the specimen has no influence on shrinkage if the surface area to volume ratio is the same (Hindy et al. 1994).

2.4.4 External factors: Effect of Curing, Temperature and Relative Humidity

Temperature and relative humidity are the main environmental factors influencing shrinkage of concrete. A decrease in rate of moisture flow from concrete to atmosphere occurs with increase in ambient relative humidity and/or decrease in ambient temperature. It is, therefore, expected that an increase in ambient relative humidity and/or decrease in ambient temperature will decrease overall shrinkage (Neville and Brooks 2003).

The effect of length of curing period on shrinkage is not clear. ACI 209.1 R-05 reports a decrease in shrinkage by 10-20% for extended periods of moist curing. The exact duration, however, is unknown. The effect of duration of initial curing period on shrinkage depends on the w/cm ratio. Powers (1959) concluded that the length of curing period has no influence on the overall shrinkage of concrete. He theorized that a longer moist curing period reduces the amount of un-hydrated cement particles. Un-hydrated cement particles help prevent shrinkage and hence longer moist curing should increase the drying shrinkage. However, microcracking of paste around the aggregates nullifies the expected increase in overall shrinkage. While the effect on ultimate autogenous shrinkage was found to be limited, the higher curing temperature led to a faster rate of autogenous shrinkage development (Lura et al. 2001).

Bennett and Loat (1970) found the impact of curing to be more pronounced for fine-grained cements (4900 cm^2/g and 7420 cm^2/g) than coarse-grained cements (2770 cm^2/g). The method adopted for curing also affects overall shrinkage of concrete. Sprinkling concrete with water twice a day or covering concrete with burlap are more effective in reducing long-term shrinkage than covering with impervious polyethylene sheets (Alsayed and Amjad 1994).

2.4.5 Entrained Air Content

The addition of air content up to 8% in concrete is reported to have no effect on drying shrinkage (ACI 209.1 R-05). However, for 2 to 8% total air content, Yurdakul et al. (2014) found the use of air entrainment to increase shrinkage for binary- and ternary-blended concrete mixtures. Piasta and Sikora (2015) attributed the increase in paste volume and porosity of interfacial transition zone (ITZ) around air voids as the cause of increase in shrinkage with air entrainment.

2.4.6 Supplementary Cementitious Materials

Mineral admixtures such as silica fume, fly ash and ground-granulated blast-furnace slag are the most commonly used supplementary cementitious material. These materials are used to increase the strength and durability of concrete. Addition of these admixtures tends to increase the volume of fine pores. Since shrinkage is related to loss of water from these pores, mineral admixtures increase shrinkage (Mehta and Monteiro 2006). Also, specific gravity of these admixtures is less than cement and hence, for an equivalent replacement by mass, more volume of these admixtures would be needed resulting in increased paste volume and, therefore, should increase shrinkage.

Contradictory reports on the effect of silica fume have been reported. ACI 209.1 R-05 reports a decrease in shrinkage for silica fume replacement less than 7.5% by weight. Silica fume have a more pronounced effect on autogenous shrinkage than drying shrinkage (Siddique 2011). Li et al. (2002) found that although concrete containing silica fume had lower drying shrinkage, they had greater autogenous shrinkage than concrete without silica fume. They explained that more water is consumed at a faster rate due to large surface area of silica fume particles leading to densification of hydrated cementitious paste and refined pore size. This leads to higher autogenous shrinkage. Removal of adsorbed water is difficult through these pores and hence drying shrinkage decreases with silica fume addition. On the opposite, several studies have found that the early-age shrinkage increases with increase in silica fume content with little to no effect on long-term shrinkage (ACI 234R-06, Khatri and Sirivivatnanon 1995).

ACI 232.2 R-96 states, if addition of fly ash increases the paste volume, drying shrinkage may increase slightly provided the water content remains constant. Due to spherical shape of fly ash particles, addition of fly ash increases workability and thus, the water content can be reduced for a given workability. They report that up to 20 percent replacement by fly ash has no effect on drying shrinkage of concrete provided the advantage of increased workability is accounted for by reducing water content. Kristiawan and Aditya (2015) found decrease in both drying and autogenous shrinkage with addition of fly ash. The magnitude of decrease is proportional to fly ash content. The decrease in shrinkage is attributed to decreased cement content, water content and refinement of pore sizes. ACI 233R-95 states that the addition of ground-granulated blast-furnace slag would increase shrinkage if the paste volume is increased. Similar observations were made by different researches (Li et al. 2002).

3.0 METHODOLOGY

3.1 ASTM C-157 Recommended Test Conditions and Procedures

ASTM C-157 standard describes test conditions for measuring free shrinkage of mortar and concrete specimens made in laboratory only. Conditions and methods to attain them are described for initial 24-hour curing period, 28-days curing period including initial curing period and storage period. Curing of the specimen during the initial curing period shall be done in a moist cabinet or moist room having an air temperature of 73 ± 3 °F (23 ± 2 °C) and relative humidity not less than 95%. Required air temperature shall be attained by heating and cooling devices. Required relative humidity shall be attained by using fog sprays, water sprays or curtains of water on the inner walls in case of moist cabinet. The specimens shall be stored in lime-saturated water at 73 ± 3 °F (23 ± 2 °C) for a further 27 days after the initial curing. Since air storage provides a more conservative result, it is preferred to water storage. For air storage, the specimens shall be placed in drying rooms maintained at a temperature of 73 ± 3 °F (23 ± 2 °C) and relative humidity of 50±4%. Conditioned air shall be circulated into and out of the room to achieve a specified rate of evaporation adjacent to all specimens, i.e. 77±30-ml/24 hour from an atmometer or 13±5-ml/24 hour from Griffin low-form beaker. Provision shall be made to measure temperature, relative humidity and rate of evaporation. Readings shall be taken at 4, 7, 14 and 28 days along with 8, 16, 32 and 64 weeks.

3.2 Existing Laboratory Test Conditions and Procedures

Multiple laboratories in the Salt Lake City area were visited to collect information on the test procedure followed, methods to maintain the required temperature and relative humidity. Significant variation was found to exist between ASTM C-157 recommended test conditions and laboratory conditions. In practice, concrete is obtained from a ready-mix plant and molded on field. The specimens are covered with plastic and wet burlap on site. This is done to avoid moisture loss. The amount of time the specimens are kept on field, before transporting to laboratories, varies. Some laboratories use an ice chest to store the specimens covered with plastic and wet burlap on site. Significant variation in air storage conditions such as storing in temperature and relative humidity chamber, inside plastic bins covered at top, inside ice chest (open for passage of air) and cabinets were observed. Some laboratories had no humidity control device and apparatus for measuring the rate of evaporation.

3.3 Test

The concrete for the test was provided by Geneva Rock. Three laboratories were selected to perform the tests. For anonymity, the labs are named as Lab A, Lab B and Lab C. The samples were molded at the Dura-Crete plant at 1475 West 3500 South, West Valley City, Utah. Each laboratory molded its own concrete specimens. Each laboratory independently performed initial curing, curing in lime-saturated water bath and air storage of concrete specimens. The days at which shrinkage measurements were performed by each laboratory differed. Modified ASTM C-157 was used in the study. The modification was with respect to the duration of curing period after initial curing.

3.3.1 Specimen sizes

ASTM C-157 standard recommends the size of the concrete specimen to be 4 by 4 by 11 ¼ inches if all the coarse aggregates pass through a 2-inch sieve. If all the coarse aggregates pass through a 1-inch sieve, the recommended size of the concrete specimen is 3 by 3 by 11 ¼ inches.

In this study, the test specimens were 4 by 4 by 11 ¼ inches.

3.3.2 Curing procedures

Since the mixtures were casted on site, the specimens were kept on site for the duration of initial curing (1 day). Different methods were used during initial curing. Lab C covered the specimen with wet burlap and stored them inside an ice chest while Lab A and Lab B covered the specimen with wet burlap and stored them on top of the table inside a casting room at the location. After initial curing, the specimens were transported to the respective laboratories. Due to time constraints, all the specimens were stored in lime-saturated water for an additional 6 days.

3.3.3 Air storage

Different methods of air storage were done to maintain the required temperature and relative humidity. Specimens were stored inside a temperature and relative humidity chamber in Lab B, inside a cabinet in Lab C and inside a small, walk-in closet space in Lab A. The temperature and relative humidity of the walk-in closet was maintained with the help of heaters, air conditioners, humidifier and dehumidifier inside the closet. The temperature inside the cabinet was maintained by maintaining the temperature of the room where the cabinet is located. The relative humidity was maintained with the help of humidifier at the bottom of the cabinet. The temperature and relative humidity of the chamber can be controlled with the help of controls provided. Only Lab A had the apparatus to measure the rate of evaporation.

3.3.4 Measurements

There are two steps to obtain free shrinkage of concrete specimen as per ASTM C-157. This includes measurement to obtain comparator readings at any age and calculations to obtain free shrinkage at any age from the comparator readings. After the comparator readings, the free shrinkage of concrete specimen at any age was calculated using equation 1.

$$\Delta L_x = \frac{CRD - Initial\ CRD}{G} \qquad (1)$$

where:

ΔL_x = Length change of specimen at any age, %

CRD = Difference between the comparator reading of the specimen and the reference bar at any age.

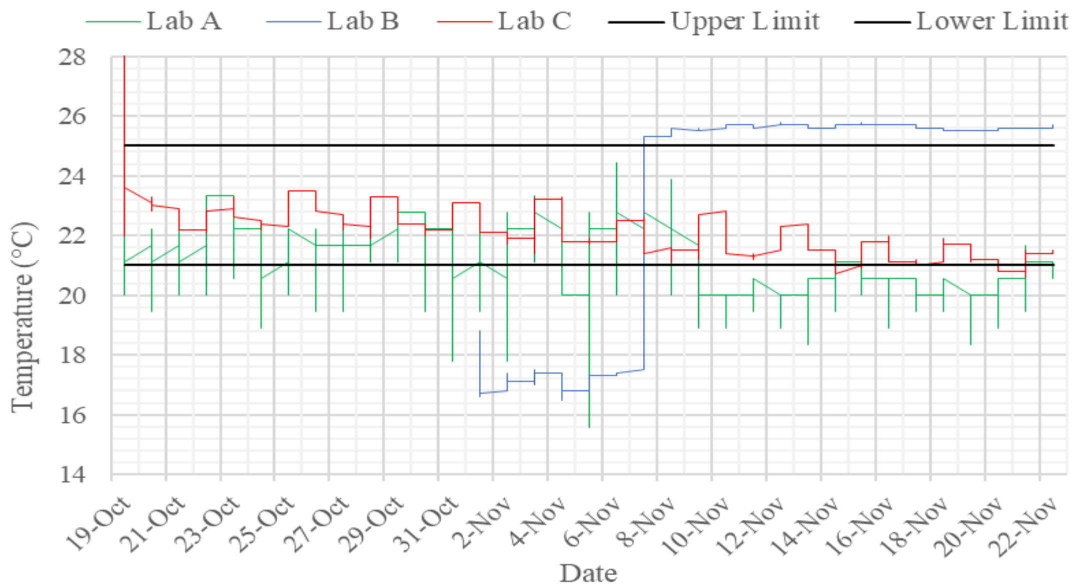
G = Gage length = 10 inches

4.0 RESULTS

4.1 Temperature and relative humidity

Figure 2 shows the temperature and relative humidity measured at different locations. Also shown in Figure 2 are the upper and lower limits of temperature and relative humidity. The temperature and relative humidity data logger used at Lab A had a resolution of 1 °F (0.5 °C) and 0.5% RH, while the other two temperature and relative humidity data loggers used at Lab B and Lab C had a resolution of 0.1 °F (0.1 °C) and 0.1% RH. Measurements were taken every hour. Temperature and relative humidity data of Lab B were measured two weeks after the start of test due to non-availability of data logger. During the tests, the temperature and relative humidity chamber broke down and hence the temperature and relative humidity could not be kept at the recommended values for Lab B. Lab C was able to keep the temperature within the limits for the majority of the test period while Lab A was unable to maintain the temperature at the latter stages of the test. Both Lab A and Lab C were unable to maintain the relative humidity within the recommended limits.

(a)



(b)

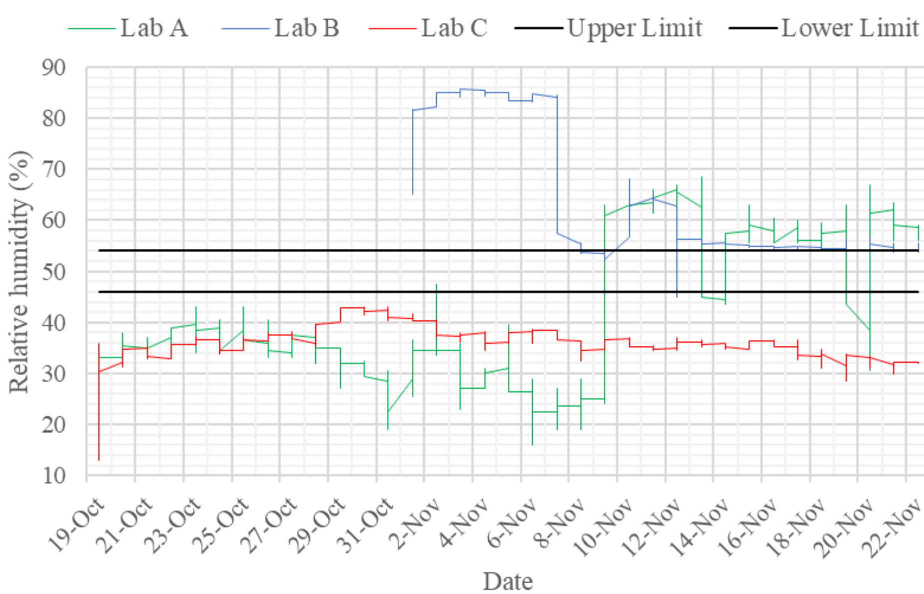


Figure 2 Data measured using data logger over the entire duration of test, excluding the initial curing period (a) Temperature (b) Relative humidity.

4.2 Shrinkage results

Table 1 shows the measured shrinkage values of concrete specimens at 28 days of air storage. Specific data of length change at each measurement date can be found in Appendix A. Lab A molded two specimens incorrectly and hence only one shrinkage measurement is available. Figure 3 shows the shrinkage variation of concrete specimens over the measured period. The concrete specimens showed both shrinkage and expansion potential. Significantly different values of shrinkage measurements were observed.

Table 1 Shrinkage measurements of concrete specimens at 28 days of air storage

Laboratory	Shrinkage at 28 days (%)			
	Specimen 1	Specimen 2	Specimen 3	Average
A	-0.0710	-	-	-0.07100
B	-0.0275	0.1155	-0.0755	0.00417
C	0.0000	-0.0040	-0.0010	-0.00167
Note: "-" indicates shrinkage				

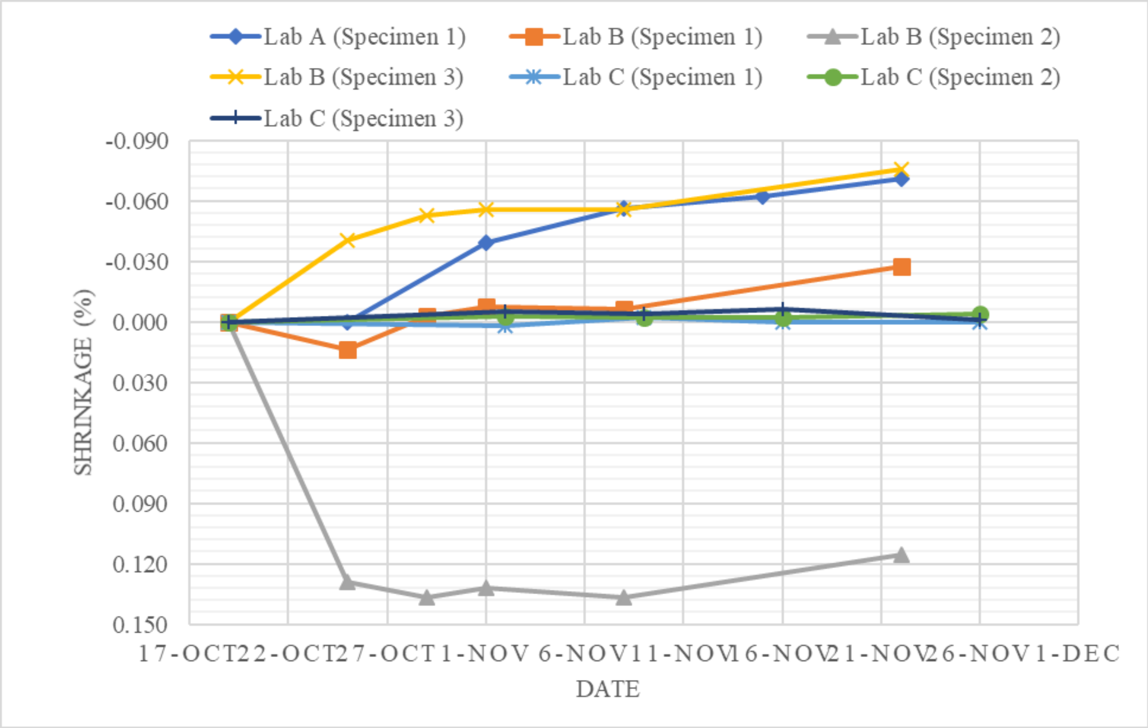


Figure 3 Change in length of concrete specimens measured over the test period.

5.0 ANALYSIS

ASTM C-157 states that for specimens stored in air, the standard deviation among the specimens tested is 0.0084 %. When three replicate specimens are tested, the maximum range among them should be less than 0.0496 % in 95 % of the sets tested. Table 2 shows the calculated standard deviation and range of the shrinkage measurements for all the laboratories. Since Lab A only had one specimen, the standard deviation and range could not be calculated. The standard deviation and range of Lab B exceeded the recommended value. However, this could be due to issues observed during testing. Lab C had the specimens' standard deviation and range within the recommended values.

ASTM C-157 also states that when a test result represents the mean of 3 specimens, the standard deviation is 0.0048 %. The results from Lab B are not considered while calculating standard deviation of the mean results. Even though the standard recommends the mean of 3 specimens for each test, the recommended standard deviation is compared with the results obtained. The standard deviation of results from Lab A and Lab C is 0.0490 %. This exceeds the recommended value. Hence the results obtained from the two laboratories are significantly different.

Table 2 Standard deviation and range of the measured shrinkage values

Laboratory	Shrinkage at 28 days (%)				
	Specimen 1	Specimen 2	Specimen 3	Standard deviation	Range
				(%)	(%)
A	-0.071	-	-	-	-
B	-0.0275	0.1155	-0.0755	**0.09936**	**0.191**
C	0	-0.004	-0.001	0.002082	0.004
Note:					
"-" indicates shrinkage					
Values in bold indicate, the value exceeds the recommended value					

6.0 CONCLUSIONS AND RECOMMENDATIONS

Shrinkage of concrete is one of the reasons for concrete cracking in bridge decks. Such cracks can be reduced by using concrete mixes with minimal shrinkage potential. This shrinkage potential was evaluated by third-party shrinkage testing laboratories as per ASTM C-157. However, significantly different results were obtained from different laboratories for the same mixes. For this reason, it was necessary to do an ASTM C-157 standard audit for third-party laboratories to improve the reliability of such results.

Three laboratories were selected to perform the ASTM C-157 free shrinkage test. The duration of the curing period was kept to 7 days, including the period in molds, due to time constraints. The temperature and relative humidity were measured using a data logger at each laboratory. The date at which shrinkage measurements were taken differed. It was observed that the labs were able to maintain the temperature within the recommended limits for most of the duration of the test. However, the relative humidity was lower than recommended limits. Moreover, the shrinkage of concrete specimens at 28 days was significantly different.

To conclude, the methods used by the laboratories to maintain the required relative humidity were not satisfactory. Different methods of initial curing, methods to maintain temperature and relative humidity have significant effect on the shrinkage measurements. To improve the reliability of the results, such differences should be eliminated, and one common accepted method should be followed by all laboratories. This would allow the use of single laboratory, multiple-operator precision values recommended in ASTM C-157 standard as a reliability check.

REFERENCES

AASHTO-PP84. (2017). "Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures Standard Practice for." *American Association of State Highway and Transportation Officials*, 1(April), 1–36.

ACI 232.2 R-96. (2002). *Use of fly ash in concrete Reported by ACI Comittee 232*.

ACI 233R-95. (2000). *Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete*.

ACI 234R-06. (2006). *Guide for the Use of Silica Fume in Concrete*.

Allahham, J., Bordelon, A., Li, L., and Rayaprolu, S. (2016). *REVIEW AND SPECIFICATION FOR SHRINKAGE CRACKS OF BRIDGE DECKS*. UDOT Research Report No. UT-16.17.

Alsayed, S. H., and Amjad, M. A. (1994). "Effect of Curing Conditions on strength, porosity, absorptivity, and shrinkage of concrete in hot and dry climate." *Cement and Concrete Research*, 24(7), 1390–1398.

Bennett, and Loat. (1970). "Shrinkage and creep of concrete as affected by the fineness of Portland cement." *Magazine of Concrete Research*, 22(71), 69–78.

Benoît Bissonnette, Pascale Pierre, and Michel Pigeon. (1999). "Influence of key parameters on drying shrinkage of cementitious materials." *Cement and Concrete Research*, 29(10), 1655–1662.

Hindy, E. El, Miao, B., Chaallal, O., and Aitcin, P.-C. (1994). "Drying Shrinkage of Ready-Mixed High-Performance Concrete." *Materials journal*, 91(3), 300–305.

Khatri, R. P., and Sirivivatnanon, V. (1995). "Effect of Different Supplementary Cementitious Materials on Mechanical Properties of High performance concrete." *Cement and Concrete Research*, 25(1), 209–220.

Kristiawan, S. A., and Aditya, M. T. M. (2015). "Effect of high volume fly ash on shrinkage of self-compacting concrete." *Procedia Engineering*, Elsevier B.V., 125, 705–712.

Li, H., Wee, T. H., and Wong, S. F. (2002). "Early-age creep and shrinkage of blended cement concrete." *ACI materials journal*, 99(1), 3–10.

Li, L. (2016). "CASE STUDIES ON FREE-DRYING SHRINKAGE TEST SENSITIVITY AND ON CARBONATION RATE OF MORTAR WITH PHOTOCATALYTICS." University of Utah.

Lura, P., Van Breugel, K., and Maruyama, I. (2001). "Effect of curing temperature and type of cement on early-age shrinkage of high-performance concrete." *Cement and Concrete*

Research, 31(12), 1867–1872.

Mcdonald, D. B., Brooks, J. J., Burg, R. G., Daye, M. a, Gardner, N. J., and Novak, L. C. (2005). *Report on Factors Affecting Shrinkage and Creep of Hardened Concrete*.

Mehta, P. K., and Monteiro, P. J. M. (2006). *Concrete Microstructure, Properties, and Materials*. *Journal of Experimental Psychology: General*, McGraw-Hill.

Neville, A. M., and Brooks, J. J. (2003). *Concrete Technology*. Pearson Education.

Piasta, W., and Sikora, H. (2015). "Effect of air entrainment on shrinkage of blended cements concretes." *Construction and Building Materials*, Elsevier Ltd, 99, 298–307.

Piasta, W., and Zarzycki, B. (2017). "The effect of cement paste volume and w/c ratio on shrinkage strain, water absorption and compressive strength of high performance concrete." *Construction and Building Materials*, 140, 395–402.

Pickett, G. (1956). "Effect of Aggregate on Shrinkage of Concrete and Hypothesis Concerning Shrinkage BY." 52(January), 581.

Powers. (1959). "Causes and control of volume changes." *Journal of the Research and Development Laboratories*, 1, 29–39.

Radlińska, A., and Weiss, J. (2012). "Toward the Development of a Performance-Related Specification for Concrete Shrinkage." *Journal of Materials in Civil Engineering*, 24(1), 64–71.

Siddique, R. (2011). "Utilization of silica fume in concrete: Review of hardened properties." *Resources, Conservation and Recycling*, Elsevier B.V., 55(11), 923–932.

Yurdakul, E., Taylor, P. C., Ceylan, H., and Bektas, F. (2014). "Effect of Water-to-Binder Ratio, Air Content, and Type of Cementitious Materials on Fresh and Hardened Properties of Binary and Ternary Blended Concrete." *Journal of Materials in Civil Engineering*, 26(6), 04014002.

Zhang, M. H., Tam, C. T., and Leow, M. P. (2003). "Effect of water-to-cementitious materials ratio and silica fume on the autogenous shrinkage of concrete." *Cement and Concrete Research*, 33(10), 1687–1694.

Zhang, W., Zakaria, M., and Hama, Y. (2013). "Influence of aggregate materials characteristics on the drying shrinkage properties of mortar and concrete." *Construction and Building Materials*, Elsevier Ltd, 49, 500–510.

APPENDIX A Shrinkage data

Table 3 Calculated length change of concrete specimen at specific time (%)

Date	Lab A	Lab B			Lab C		
	Specimen 1	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
10/19/18	0.0000	0.0000	0.0000	0.0000	0.000	0.0000	0.0000
10/25/18	0.0000	0.0140	0.1290	-0.0405	-	-	-
10/29/18	-	-0.0030	0.1365	-0.0525	-	-	-
11/01/18	0.0390	-0.0075	0.1320	-0.0555	-	-	-
11/02/18	-	-	-	-	0.002	-0.0030	-0.0050
11/08/18	0.0560	-0.0065	0.1365	-0.0555	-	-	-
11/09/18	-	-	-	-	-0.002	-0.0020	-0.0040
11/15/18	0.0620	-	-	-	-	-	-
11/16/18	-	-	-	-	0.000	-0.0020	-0.0060
11/22/18	0.0710	-0.0275	0.1155	-0.0755	-	-	-
11/26/18	-	-	-	-	0.000	-0.0040	-0.0010