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INTERNAL CURING OF HIGH PERFORMANCE CONCRETE USING LIGHTWEIGHT AGGREGATES AND OTHER TECHNIQUES

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16. Abstract

Internally cured concrete has been rapidly emerging over the last decade as an effective way to improve the performance of concrete. Internal curing (IC) holds promise for producing concrete with an increased resistance to early-age cracking and enhanced durability (Bentz and Weiss, 2011). IC is a simple and effective way to cure concrete. Proper internal curing supplies water that is necessary to relieve stress buildup due to self-desiccation. Typically this is done using pre-wetted lightweight aggregates (LWAs), as this is the most commercially available application at the present time. IC has shown reduced autogenous and drying shrinkage cracking, improved fluid absorption resistance, improved compressive strength, and reduced ion diffusion. It is becoming increasingly clear that internal curing has great potential for the concrete industry to create a longer lasting, more sustainable product.

This report specifically examines the freeze-thaw resistance of internally cured concrete. It is shown that internally cured concrete, using the recommended mixture proportions (i.e., pre-wetted fine LWAs to replace only the water lost due to chemical shrinkage) is freeze-thaw resistant.

Implementation

Internal curing has shown, as outlined in this report, to be a simple and cost-effective way to create longer lasting, more durable concrete. The initial cost of a bridge deck concrete *can* increase in price anywhere from 3 to 10 \$/yd^3. However, this percentage when compared with the cost of bridge is typically negligible, especially when considering an increased service live and reduced maintenance cost. CDOT can benefit from this research by applying what has been presented in this study to create longer lasting, more durable bridge decks.

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Submitted to the Colorado Department of Transportation

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EXECUTIVE SUMMARY AND IMPLEMENTATION

Internally cured concrete has been rapidly emerging over the last decade as an effective way to improve the performance of concrete. Internal curing (IC) holds promise for producing concrete with an increased resistance to early-age cracking and enhanced durability (Bentz and Weiss, 2011). It is a simple and effective way to cure concrete. Proper internal curing supplies water that is necessary to relieve stress buildup due to self-desiccation. Typically this is done using pre-wetted lightweight aggregates (LWAs), as this is the most commercially available application at the present time. IC has shown reduced autogenous and drying shrinkage cracking, increased fluid absorption, improved compressive strength, and reduced ion diffusion. It is becoming increasingly clear that internal curing has great potential for the concrete industry to create a longer lasting, more sustainable product.

The goal of this study was to reproduce Colorado DOT bridge deck mixtures and to alter these mixtures by replacing portions of normal-weight aggregate (NWA) with various amounts, sizes, and suppliers of pre-wetted LWA. To produce similar mixtures, materials common to, and available in, the Colorado area were obtained and used in this study. Material suppliers for this project are as follows: Aggregate Industries (NWA); Holcim US, Inc. (cement); Headwaters Resources (fly ash); TXI/ Trinity Expanded Shale and Clay (coarse and fine LWA); Utelite Corp. (fine LWA); Buildex, Inc. (fine LWA). The research focused on comparing the fresh, mechanical, freeze-thaw, shrinkage, and transport properties, with an emphasis on cyclic freezing and thawing durability. While many internally cured mixtures were investigated in this study, the report presented recommends a mixture design that supplies the amount of water lost due chemical shrinkage by replacing a portion of the normal-weight fine aggregate with fine LWA. This allows for proper spatial distribution of the porous inclusions used in hydration the cement.

Obtaining the correct absorption and moisture contents in the LWA particles are an essential part of creating quality IC mixtures. Two methods were discussed, however it is the opinion of the authors that the centrifuge method (Miller et al., 2013) is the most consistent method for obtaining the moisture content and surface moisture. Internally cured mixtures do not have a significant impact on the slump, although some have noticed improved workability. The pressure method is generally the preferred method for testing air content of fresh concrete since it is easier to perform in the field, although about a 10% variance from the volumetric method is noticed. Note that one would use the volumetric method for testing air content due to porous aggregates, however the pressure method works and is significantly faster. For the recommended IC mixtures the unit weight is not significantly altered, he largest difference being mixture 6 with a decrease by 8%, with the other recommended mixture only decreasing around 2%. In compression the IC mixtures performed similarly, and in some cases showed an improvement up to about 10%, when compared to the standard mixture. The compressive strength of all mixtures was above the values specified by Colorado DOT specifications. This can be attributed to the increased hydration created through internal curing. All IC mixtures showed a reduction in the modulus of elasticity (about 10 – 20%), which will actually benefit mixtures in reducing shrinkage cracking. These results of freeze-thaw testing show that properly air entrained, internally cured concrete with a reasonable w/c have no issues in resisting cyclic freeze-thaw action. However, “excessively” internally cured mixtures, i.e., mixtures that have more pre-wetted LWA than is required to replace water lost due to chemical shrinkage, show up to a potential reduction in durability when compared with the standard Class H mixture. Scaling results showed that internally cured mixtures do not perform any worse than the standard mixtures. Internally cured mixtures minimize autogenous shrinkage and cause expansion (or swelling) in a sealed system. This expansion will eventually relax out over time. Restrained shrinkage showed that IC concrete reduced the residual stress buildup in the material, however this was not as apparent in these “higher” w/c mixtures as it would be when comparing a lower w/c with the IC counterpart. Internally cured mixtures show improved drying shrinkage performance, since water is present in the matrix to continue hydration as the surface dries. Internally cured concrete reduces the chloride diffusion coefficient and pore tortuosity up to 67% compared to standard mixtures, which is attributed to increased hydration and reduced interfacial transition zone (ITZ) percolation. Permeability is also decreased when the recommended IC mixture is used. Sorption properties are comparable from recommended IC mixtures.

This report, along with presenting the benefits of internal curing, provides mixture guidelines for internally cured concrete for commercial use in Colorado. Internal curing has shown, as outlined in this report, to be a simple and cost-effective way to create longer lasting, more durable concrete. The initial cost of a bridge deck concrete *can* increase in price anywhere from 3 to 10 $\$/yd^3$. However, this percentage when compared with the cost of bridge is typically quite low, especially when considering the benefits of an increased service live and reduced maintenance cost. The Colorado DOT can benefit from this research by applying what has been presented in this study to create longer lasting, more durable bridge decks.

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CHAPTER 1. INTRODUCTION TO INTERNAL CURING

1.1 Background

Internally cured concrete has been rapidly emerging over the last decade as an effective way to improve the performance of concrete. Internal curing (IC) holds promise for producing concrete with an increased resistance to early-age cracking and enhanced durability (Bentz and Weiss, 2011). The technique of IC has recently been studied and used in several field applications (Schindler, Grygar, and Weiss, 2012). As of 2010, hundreds of thousands of cubic meters of concrete containing pre-wetted lightweight aggregates (LWAs) for the use of internal curing have been placed throughout the United States (Bentz and Weiss, 2011).

1.1.1 A Brief History

Before discussing the theory of IC, one should first know a little about how IC developed. The use of LWAs in concrete has existed since the early Roman times, where natural lightweight concrete had been used in structures such as the Pantheon (Bremner and Ries, 2009). These lightweight concretes may have, unknowingly, benefitted from what is now known as internal curing and provides some explanation to the outstanding durability of a few of these ancient structures.

It is believed that the first published notion that LWA can provide additional moisture to the cementitious system was in 1957 by Paul Klieger. He stated “Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration” (Klieger, 1957). However, research on internal curing did not really progress until 1991 when Robert Philleo stated, “Either the basic nature of portland cement must be changed so that self-desiccation is reduced, or a way must be found to get curing water into the interior of high-strength structural members... ”. The idea of placing water inside of concrete is “…possible through the use of prewetted LWA.” However, it is not intuitive to introduce LWA, a highly porous material, into concretes that are to achieve higher strengths. Therefore, those striving for higher strength concretes are generally not receptive to the idea of introducing LWA into the cementitious system. However, Philleo suggested, “A partial replacement of fine aggregate with saturated lightweight fines might offer a promising solution” (Philleo, 1991). Since then, pre-wetted LWA has been studied and applied in the field to improve the curing process of concrete (Weber and Reinhardt, 1996; Bentz and Snyder, 1999; Bentur et al., 2001; Jensen and Hansen, 2001; RILEM, 2007; Radlinska, 2008; Schlitter et al., 2010; Bentz and Weiss, 2011).

1.1.2 How Internal Curing Works

While the concept on internal curing is very simple, the science behind it is quite interesting. The American Concrete Institute (ACI) has defined internal curing as “[the] process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water” (America Concrete Institute, 2013). Internal curing essentially consists of hiding water inside the concrete without altering the porosity of the paste. This hidden and dispersed water is available to the system as needed for hydration, after the time of set.

As demonstrated in Figure 1.1, external curing water (surface-applied water) may only penetrate a few millimeters into high performance concretes (Weiss et al., 1999; Bentz, 2002). Internal curing, with proper spatial distribution and an appropriate amount of water, can create a three dimensional microstructure in which the hydrating cement paste remains at a high relative humidity (Bentz and Weiss, 2011). A basic illustration of the difference between internal and external curing can be seen in Figure 1.1.

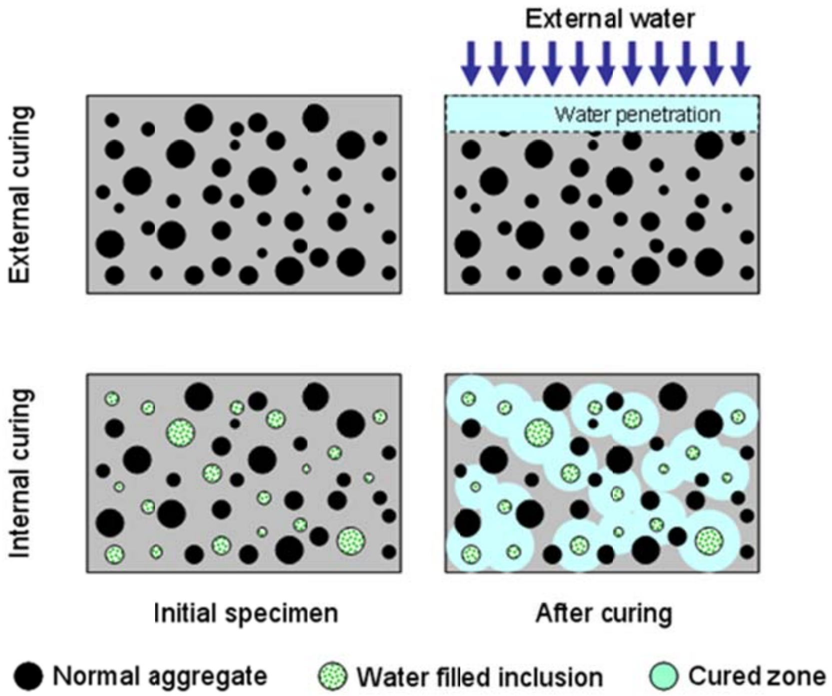


Figure 1.1: Conceptual illustration to show the difference of external and internal curing (Castro et al., 2011)

In order for internal curing to be effective, the water filled inclusions should be distributed throughout the concrete and spaced close enough to provide coverage for the entire paste system (Henkensiefken et al., 2008; Castro et al., 2010). The water provided to the cementitious matrix is done via the use of water filled inclusions. The key to internal curing is that the water being released is time delayed. This effect is dependent on the size of the pores in the LWA. The pores need to be a size such that water is taken in and held during the mixing process (absorption), but can be released from the pores back into the paste after setting, when needed for curing (desorption).

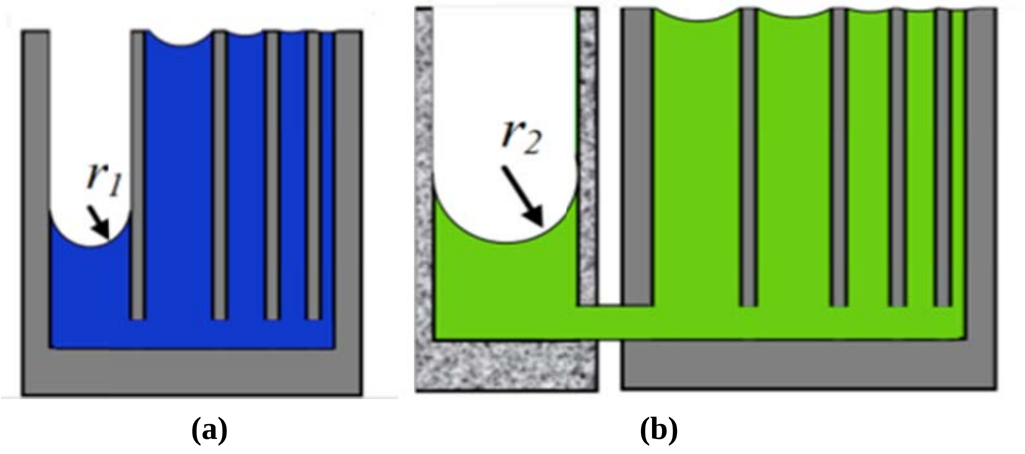
Figure 1.2 illustrates how the pores of a cementitious system are emptied during chemical shrinkage. Figure 1.2 (a) indicates a standard mixture without internal curing. Here the pores of the system are emptied from largest to smallest. Figure 1.2 (b) shows that when a porous material (such as LWA) with larger pores than those found in the microstructure of the paste is added into the system, water is drawn from these larger pores in the LWA due the negative pressure buildup from self-desiccation in the paste. This water from the porous material replaces what is lost in chemical shrinkage and will in theory fully hydrate the cement matrix. When a sufficient volume of LWA is used, with adequate desorption properties and spatial distributions within the matrix, enough water can be provided throughout the cementitious matric to prevent early age cracking in the concrete system.

1.2 Motivation for Its Use

Internal curing was originally promoted to reduce autogenous shrinkage and autogenous shrinkage cracking (Bentz and Snyder, 1999; Jensen and Hansen, 2001; Kovler and

Jensen, 2005; Radlinska et al., 2007; RILEM, 2007; Lopez et al., 2008). Autogenous shrinkage is a phenomenon caused by chemical shrinkage, independent of external drying. However, the benefits go well beyond the reduction of autogenous shrinkage.

Recent work has demonstrated benefits of internal curing for reducing drying shrinkage, drying shrinkage cracking (Henkensiefken et al., 2008; Henkensiefken et al., 2009), and improved plastic shrinkage cracking resistance (Henkensiefken et al., 2010). Internal curing can also increase the resistance to fluid absorption (Bentz and Snyder 1999, Henkensiefken et al. 2009, Peled et al. 2010), improve the compressive strength (Golias et al., 2012) and reduce ion diffusion (Bentz, 2009; DiBella et al., 2012) in concrete. It is becoming increasingly clear that internal curing has great potential for the concrete industry to create a longer lasting, more sustainable product.



(a) **(b)**

Figure 1.2: Illustration demonstrating how water is emptied from largest pores to smallest. (a) Shows a standard cementitious system and (b) shows a cementitious system using internal curing, where the pore on the left side of the image is that of the lightweight aggregate.

1.3 Research Objectives

The use of internal curing in high performance concrete can increase the resistance to early-age cracking and enhance its durability (Bentz and Weiss, 2011). However, questions have been raised about the freeze-thaw durability of these concretes. The objective of this study is to investigate the freeze-thaw performance of internally cured, high performance concrete for use by the Colorado Department of Transportation (CDOT). In particular, this study evaluates a series of internally cured, high performance concrete mixtures that meet the specifications of Colorado DOT Class H and Class D bridge deck concretes.

This study investigates the use of LWA for internal curing and quantitatively shows the impact of LWA on the freeze-thaw performance for these mixtures. Specifically, this study has been divided into two phases. The first phase of the work investigates the freeze-thaw response of a typical Class H concrete mixture and a typical Class H mixture where varying portions of the normal aggregate is replaced with LWA. The second phase of the work investigates the freeze-thaw behavior of a typical Class H concrete mixture using two additional LWAs that are available in the Colorado market. The second phase of the research will also develop and evaluate an internally cured concrete that meets the Colorado DOT Class D specification.

Aside from evaluating the freeze-thaw related performance of these mixtures, this report encompasses and discusses all areas that make internal curing beneficial. The fresh, mechanical, shrinkage, and transport properties of these mixtures have been investigated and are presented in this report. In addition to simply performing and reporting experimental evaluations, this report describes the principles that make internally cured concrete beneficial and resistant to freezing and thawing behavior, so that specifications can be developed by the Colorado DOT for producing durable, long lasting, concrete using internal curing.

CHAPTER 2. CHARACTERIZATION OF MIXTURES USING INTERNAL CURING FOR COLORADO

2.1 Evaluated Mixtures

As previously noted, this study is split into two phases. Phase I evaluates preliminary mixtures comparing the Colorado DOTs typical Class H concrete mixtures to Class H mixtures that are internally cured, using a variety of approaches. Phase II evaluates optimized IC mixtures, being the Colorado DOTs Class H mixtures using alternative LWA sources as well as typical and IC Class D mixtures.

2.1.1 Phase I Mixtures

Phase I evaluates five mixtures to compare the performance of a Class H Colorado bridge deck mixture with Class H mixtures that are designed to utilize internal curing concepts. The IC mixtures for this phase will use LWA from a single supplier. These mixtures are as follows:

1. A mixture consistent with the standard Class H Colorado DOT bridge deck mixture,
2. A mixture similar to the standard Class H Colorado DOT bridge deck mixture where a portion of the fine aggregate is replaced by fine LWA (where enough LWA is used to replace the water lost by chemical shrinkage, i.e., the typical

value used for IC),[*]

3. A mixture similar to the standard Class H Colorado DOT bridge deck mixture where a portion of the fine aggregate is replaced by fine LWA (where enough LWA is used to replace twice the water lost by chemical shrinkage),
4. A mixture similar to the standard Class H Colorado DOT bridge deck mixture where a portion of the coarse aggregate is replaced by coarse LWA (where enough LWA is used to replace the water lost by chemical shrinkage), and
5. A mixture similar to the standard Class H Colorado DOT bridge deck mixture where a portion of the coarse aggregate is replaced by coarse LWA (where enough LWA is used to replace the water lost by chemical shrinkage and the aggregate spacing provides that all of the paste is within 2 mm of the surface of a LWA).[†]

Phase I testing provides information on the fresh, mechanical, shrinkage and cracking, and fluid transport properties of the internally cured concrete as it compares with the standard Colorado DOT Class H Mixture. This work specifically offers information on the aggregate absorption and desorption properties as well as the freeze-thaw behavior of these mixtures. The desorption behavior of the aggregates are used with relative humidity (RH) measures in the mixture to describe the water that is given back to the system by the LWA. Additionally, the water absorption measurements of the system are

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[*] This is the typical way internal curing has been performed following the procedure outlined by Bentz and Snyder (Bentz and Snyder, 1999)

[†] Only 92% of the paste was protected within a 2mm distribution around the aggregate even when all of the coarse NWA was replaced with coarse LWA. This will be further explained in Section 2.4.

used to compute the degree of saturation for the purpose of describing the susceptibility that these mixtures may have to freeze-thaw damage (Li et al., 2011).

2.1.2 Phase II Mixtures

Phase II consists of using the two alternative LWA sources in mixtures similar to the standard Class H Colorado DOT mixture used in Phase I where a portion of the fine aggregate is replaced by fine LWA (where enough LWA is used to replace the water lost by chemical shrinkage); similar to mixture 2. This is done because of differences in absorption and gradation that can be expected between these sources (Castro et al. 2010). In addition, a conventional Colorado DOT Class D mixture was be prepared along with an internally cured Class D mixture (where enough LWA is used to replace the water lost by chemical shrinkage). All of the testing procedures described for Phase I are used in evaluating Phase II mixtures.

2.2 Materials and Suppliers

Internal curing is generally performed in the United States using expanded LWAs (shale, clay, slate, and slag). Other materials have been proposed that could function as internal water reservoirs such as super absorbent polymers (SAPs), cellulose and plant fiber, and recycled concrete. Work has specifically been done on superabsorbent polymers (SAPs) (Jensen and Hansen, 2001; Jensen and Hansen, 2002; Schlitter and Barrett, 2010) and pre-wetted wood fibers (Mohr et al., 2005). It is the opinion of the investigation team that the most commercially ready products for DOT applications are expanded fine LWA; however other material may be ready for use in the near future.

It is the goal of this study to provide the Colorado DOT with mixture proportions for a high performance, internally cured concrete that is ready for use in a field application. In order to do so, it is crucial to perform the described testing on mixtures that would be typical to a Colorado bridge deck. This means utilizing constituent materials standard to the area, as well as LWA from a source(s) that would be practical for use in Colorado. Table 2.1 shows a list of the materials used in this study, including the suppliers and their location.

Table 2.1: Material used in this study, including the supplier and location.

Supplier	Material Used*	Location
Aggregate Industries	Morrison Pit Size 57/67	Golden, CO
Aggregate Industries	Thorton Pit Washed Concrete Sand	Golden, CO
Holcim US, Inc.	Type I/II OPC	Golden, CO
Headwaters Resources	Class F Fly Ash	South Jordan, UT
TXI/ Trinity ESC	3/8” Structure Coarse (LWA)	Boulder, CO
TXI/ Trinity ESC	Structural Fines (LWA)	Boulder, CO
Utelite Corp.	Structural Fines (LWA)	Coalville, UT
Builidex, Inc.	Structural Fines (LWA)	Marquette, KS

* Certain commercial equipment, instruments, or materials are identified in this report in order to foster understanding. Such identification is not intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

TXI LWAs (now Trinity Expanded Shale and Clay, but will be referred to as TXI throughout this report as this was the company name when the study began) were used as the primary LWA supplier. Utelite and Buildex LWAs were also used in this study to show that internally cured concrete can be equally as effective with multiple LWA suppliers and to point out variations that can arise between them.

2.3 Proportioning for Internal Curing with LWA

Previous studies have shown that there are three key considerations for determining the mixture proportions of an internally cured concrete (Bentz et al., 2005; Henkensiefken et al. 2008):

1. How much internal curing water is necessary (the amount is related to the volume of chemical shrinkage exhibited by the matrix),
2. How far into the surrounding cement paste the needed water can readily travel, and
3. How the LWA reservoirs are spatially distributed within the concrete.

A procedure has been developed (discussion to follow) that uses these three concepts in determining the mixture proportions of concrete mixtures using LWA to provide water for internal curing. The investigative team utilized this procedure in creating the mixture designs for the concretes under evaluation. Research by Castro et al. (Castro et al., 2010) and Pour Ghaz et al. (Pour Ghaz et al., 2012) investigated the properties of LWAs from various material suppliers across the US, using several techniques that can be applied to internal curing. This work will utilize newly developed standard procedures, ASTM

C1761 (2012), to measure the absorption and desorption properties of the LWA so that these properties can be correctly included in the mixture design.

The most basic way to explain proportioning of internal curing is the classic economics principle of supply and demand; the water lost in the system to chemical shrinkage (or self desiccation) creates a *demand* in the system, which is to be *supplied* by internal curing. An equation for evaluating the demand (left side) and supply (right side) has been developed by Bentz et al. (Bentz et al., 1999; Bentz et al., 2005) and is shown in Equation (2.1a) below. By rearranging Equation (2.1a), a solution for the mass of oven dry LWA required for internal curing is produced, seen in Equation (2.1b).

$$C_f * CS * \alpha_{max} = S * \Phi_{LWA} * M_{LWA} \qquad (2.1a)$$

$$M_{LWA} = \frac{(C_f * CS * \alpha_{max})}{(S * \Phi_{LWA})} \qquad (2.1b)$$

In Equation (2.1a) and (2.1b), C_f is the cement (or binder) factor of the concrete mixture, CS is the chemical shrinkage of the binder at 100 % reaction, α_{max} is the expected maximum degree of reaction for the binder (ranging from 0 to 100 %), M_{LWA} is the mass of oven dry LWA, which is based on their saturation level relative to a quantified ‘pre-wetted’ condition, S, and the measured sorption capacity of the internal reservoirs when in a pre-wetted condition, Φ_{LWA}. This equation represents the amount of internal curing water to be required by the system based on these inputs.

2.4 Spatial Distribution for Internal Curing with LWA

In order to optimize the design of internal curing mixtures, an understanding of the distance traveled by water from the internal reservoirs (LWA) to the unhydrated cement paste must be obtained (Bentz and Weiss, 2011). An estimated water travel distance can be determined using a web-based modeling program on the NIST internal curing website. The model is based on an analysis first developed by Weber and Reinhardt (Weber and Reinhardt, 1999). This model estimates the expected water travel distance, obtained by equating the projected water flow rate to a value needed to maintain saturation in the surrounding cement paste at its current rate of hydration.

The obtained travel distance is then used on a hard core/soft shell computer code (Bentz, Garboczi, and Snyder, 1999), available on the NIST internal curing website, to estimate the amount of ‘protected paste’ in the matrix. Protected paste refers to the percentage of hydrating cement paste that can be reached from the traveling water by internal reservoirs. In this model, a water travel distance of 2mm from the face of the LWA material is assumed, which is a reasonable estimate for late age (3 - 7 days) hydrating paste (Bentz et al., 2007).

Figure 2.1 shows generalized (aggregate absorption/ desorption properties are constant) modeling outputs for each of the LWA replacements for this projects mixture designs. The program receives an input based on aggregate gradations and the percentage of LWA to be replaced for a specific gradation. The program then randomly assigns aggregates to a location in a 3cm by 3cm space, which are the images shown in the Figure 2.1 (a) – (d).

Table 2.2 (a) – (d) are the corresponding output values of protected paste fractions to the models in Figure 2.1, at specified distances from the LWA particles. A value of 1.0 indicates that all of the cement paste within that specified distance of a LWA surface can obtain full hydration.

Figure 2.1 (a) shows that when coarse LWA is used to replace the water lost by chemical shrinkage no lightweight particles are present in the output image. This is due to the scarcity of coarse lightweight that would be used in replacing chemical shrinkage water. This is where particle spacing becomes very important for internally cured mixtures, as curing water must be properly distributed throughout the matrix for proper cement hydration. Figure 2.1 (b) illustrates a 100% coarse aggregate replacement of pre-wetted LWA. Table 2.1 (b) shows that a 2mm moisture distribution (protected paste value of 1.0 at 2mm) cannot be obtained with coarse LWA. A 0.92 (or 92%) protected paste value is achieved with 100% replacement of coarse LWA. Figure 2.1 (c) illustrates a mixture in which pre-wetted fine LWA is used to replace the water lost to chemical shrinkage. Figure 2.1 (d) illustrates a mixture in which pre-wetted fine LWA is used to replace twice the water lost to chemical shrinkage.

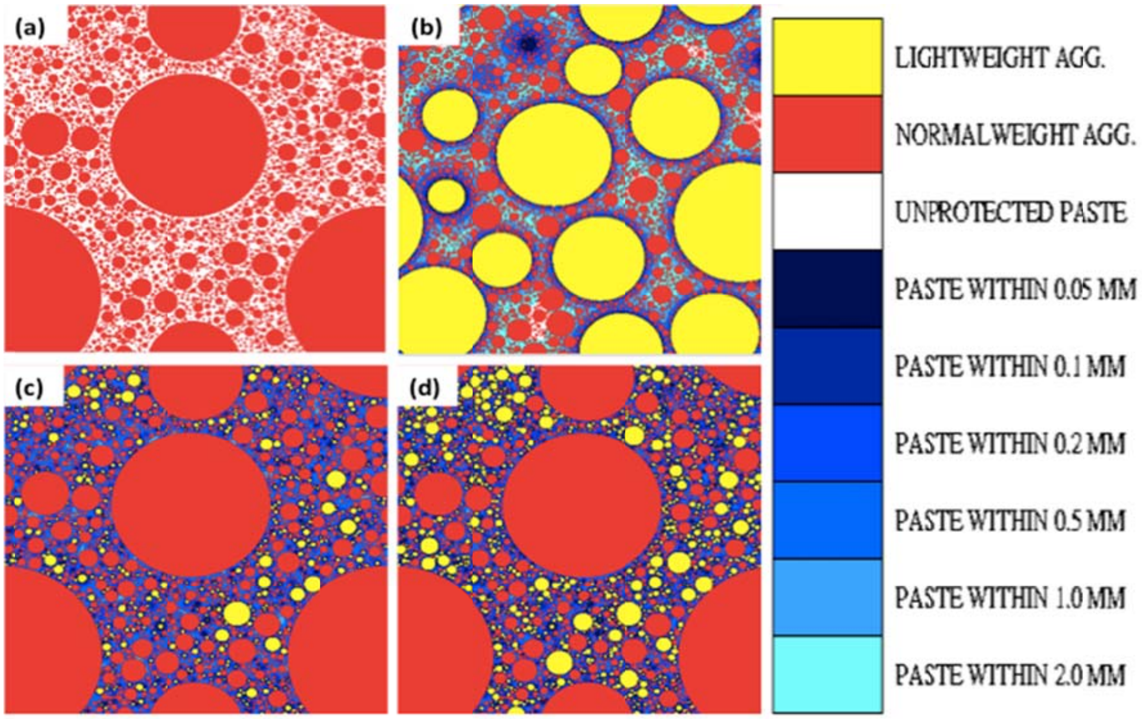
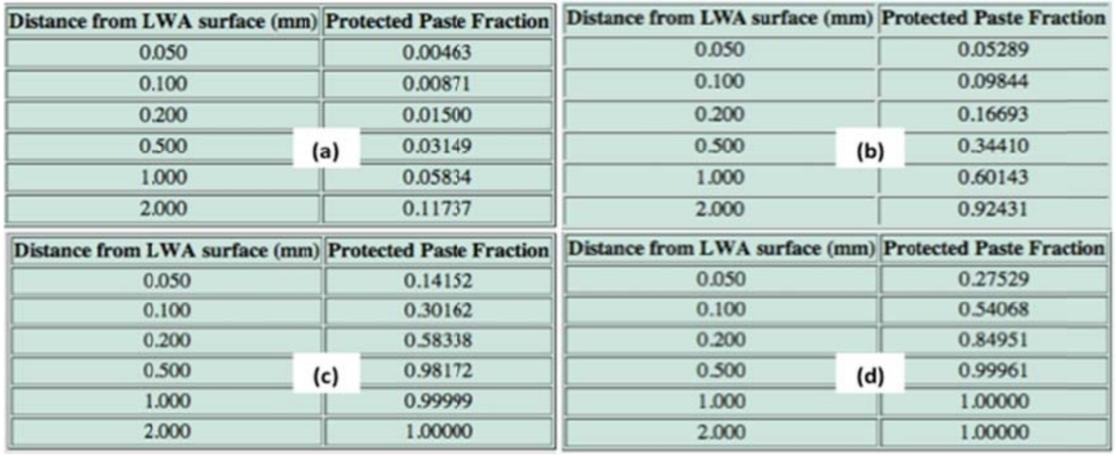


Figure 2.1: NIST IC simulation, which illustrates paste hydration when (a) coarse LWA is used to replace the water lost by chemical shrinkage, (b) 100% coarse LWA is used to replace normal coarse aggregate, (c) fine LWA is used to replace the water lost to chemical shrinkage, and (d) fine LWA is used to replace twice the water lost to chemical shrinkage.

Table 2.2: Protected paste volume as a function of distance from the LWA surface, corresponding to Figure 2.1, where (a) coarse LWA is used to replace the water lost by chemical shrinkage, (b) 100% coarse LWA is used to replace normal coarse aggregate, (c) fine LWA is used to replace the water lost to chemical shrinkage, and (d) fine LWA is used to replace twice the water lost to chemical shrinkage.



(a)

Distance from LWA surface (mm)	Protected Paste Fraction
0.050	0.00463
0.100	0.00871
0.200	0.01500
0.500	0.03149
1.000	0.05834
2.000	0.11737

(b)

Distance from LWA surface (mm)	Protected Paste Fraction
0.050	0.05289
0.100	0.09844
0.200	0.16693
0.500	0.34410
1.000	0.60143
2.000	0.92431

(c)

Distance from LWA surface (mm)	Protected Paste Fraction
0.050	0.14152
0.100	0.30162
0.200	0.58338
0.500	0.98172
1.000	0.99999
2.000	1.00000

(d)

Distance from LWA surface (mm)	Protected Paste Fraction
0.050	0.27529
0.100	0.54068
0.200	0.84951
0.500	0.99961
1.000	1.00000
2.000	1.00000

CHAPTER 3. EVALUATION OF MATERIAL PROPERTIES

3.1 Introduction

The goal of internal curing is to provide water that will fill the empty space that would be formed in the portion of pores that are emptied due to self-desiccation. Before assessing the performance of cementitious systems utilizing internal curing, it is first necessary to characterize the constituent materials. The goal of this chapter is to characterize the materials used in this study, both standard Colorado DOT materials and LWAs available in the Colorado market that could be used for internal curing in Class H and D mixtures.

3.2 Constituent Material Properties

Table 2.1 provides the list of materials used in this study. From this point forward in the report the 57/67 Morrison Pit Aggregate will be referred to as simply coarse aggregate, or CA. Similarly the Thorton Pit washed sand as fine aggregate, or FA. Type I/II OPC as cement and Class F fly ash as fly ash.

In order to create a mixture design, specific gravities of the aforementioned constituent materials and absorptions of the aggregates must first be obtained. The values can be seen in Table 3.1. The manufacturer provided specific gravity for the cement and fly ash. Saturated surface dry (SSD) specific gravity and absorption of the coarse and fine aggregates were determined in accordance with ASTM C127 (2012) and ASTM C128 (2012), respectively.

Table 3.1: SSD specific gravity and absorption, by mass, of constituent materials used in mixture designs

Material	**S.G.**	**Abs., %**
Cement	3.15	-
Fly Ash	2.37	-
Coarse Aggregate	2.65	0.80%
Fine Aggregate	2.62	1.10%

3.3 LWA Properties

3.3.1 A Discussion of Testing Procedures for LWA

Determining the properties of LWAs can become problematic since an SSD condition really does not exist. It is more appropriate to determine the properties for a pre-wetted surface dry condition. ASTM C1761 (2012) provides a method for determining absorption, specific gravity/ relative density, and desorption based on obtaining pre-wetted conditions, after a 72-hours soaking time, similar to ASTM C127 (2012) for fines and ASTM C128 (2012) for coarse. These methods both rely heavily on the users interpretation of the ‘SSD’ state of the aggregates and consequently create large variations in materials with high absorptions.

Work by Miller et al. (Miller et al., 2013) provides a simple and repeatable method for obtaining pre-wetted surface dry conditions in aggregates via the use of a centrifuge.

LWAs were tested for 72-hour absorption using both the paper towel method provided by ASTM C1761 (2012) as well as the centrifuge method. The centrifuge method consists of spinning approximately 500 grams of soaked LWA for 3 minutes at a speed of 2000 revolutions per minute (rpm). Absorption, specific gravity, and desorption are then tested in same manner prescribed by ASTM C1761 (2012) to provide properties for a pre-wetted surface dry condition after 72-hours of soaking.

3.3.2 Absorption and Specific Gravity

Accurate absorption values are a key component in creating a quality internally cured mixture design. If absorption values of the LWA are underestimated, an overabundance of water is being provided to the matrix, which can increase the water-cement ratio during the mixing phase. This will results in a high water-cement ratio. If absorption values of the LWA are overestimated, not enough water will be present in the LWA to replace that lost to chemical shrinkage, therefore not providing sufficient water for internal curing. Values for absorption and specific gravity used in the mixture designs for this study can be found in Table 3.2. While a 72-hour soaking time has been prescribed by the standard for consistency purposes, the authors prefer a 24-hour soaking time for certain laboratory tests. Both values are reported in Table 3.2. It should be noted that values for specific gravity are linked to the moisture state of the aggregates and would theoretically change from a 24 hours soaking period to a 72 hour soaking period. However, the slight change in specific gravity has not been accounted for in this study.

Table 3.2: Specific gravity and absorption, by mass, of LWA materials used in mixture designs

Material	SG*	24hr, %	72hr, %
TXI, CA	1.74	15.0%	17.5%
TXI, FA	1.85	16.5%	18.5%
Buildex, FA	1.65	16.5%	18.7%
Utelite, FA	1.87	18.8%	19.9%

*Specific gravity (SG) measured from aggregates that have undergone a 72 hour soaking period.

3.3.3 Desorption

Desorption is the loss of water from the LWA pores to the concrete matrix. This process (i.e., the release of water from the LWA pores into the matrix) is what makes internal curing possible. A desorption isotherm, a plot of mass loss as a function of time keeping temperature and RH constant (23 ± 1 °C [73.5 ± 1.5 °F] and 94 ± 0.5%, respectively) is shown in Figure 3.1 to show how this process works. The desorption curve was created in accordance with ASTM C1761 (2012), where aggregate started in a pre-wetted condition, after a 72-hour soaking period, using both the “paper towel method” described in ASTM C1761 (2012) as well as the centrifuge method described in Section 3.3.1. Values presented in this section are averages of both methods. Once in an SSD condition samples of approximately 5g and 20g for LWFA and LWCA, respectively, were weighed into a dish and placed in the constant RH chamber at 94 ± 0.5%. The masses were monitored daily until no more than a 0.01g change in mass occurred. The samples were then placed in an oven to obtain the oven dry mass from which desorption can be calculated. A value of 0 in Figure 3.1 indicates an aggregate that has desorbed all of its water, i.e., an aggregate in an oven dry state. An efficient LWA describes one that desorbs the majority of the water it absorbs, approximately 85%. The average final desorption values (percent desorbed) and standard deviation in for each aggregate can be seen in Table 3.3. The values presented in the plot represent an average of four specimens from the same aggregate, two specimens utilizing the paper towel method and two the centrifuge method.

Table 3.3: Desorption of LWA used in this study

LWA	% Desorbed (Total)	% Desorbed (Paper Towel)	% Desorbed (Centrifuge)	SD, ± %
Txi, CA	89%	90%	87%	2.2%
Txi, FA	91%	91%	92%	1.8%
Buildex, FA	97%	97%	96%	1.3%
Utelite, FA	90%	91%	90%	2.3%

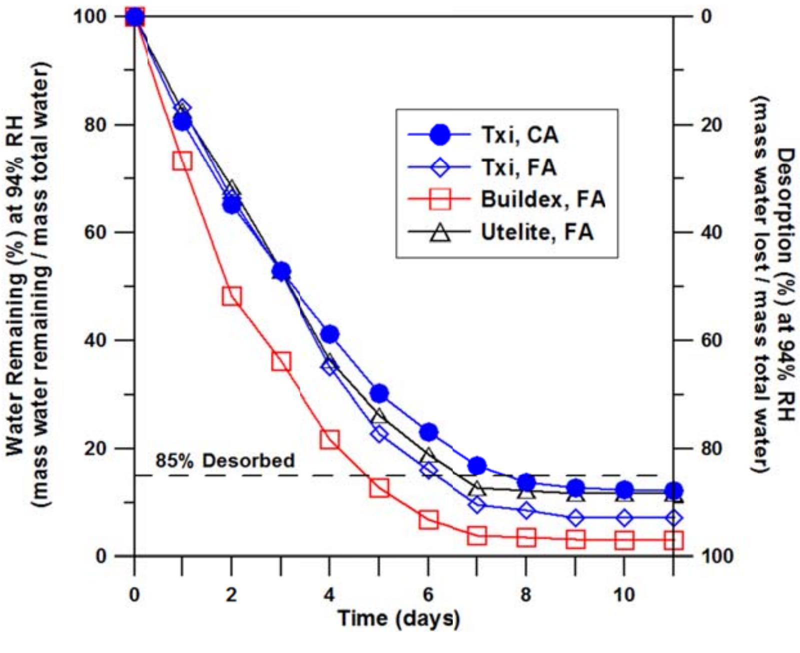


Figure 3.1: Desorption isotherm for LWAs used in this study.

3.4 Coarse Aggregate Gradations

Gradations for the coarse aggregates, both standard and lightweight, were obtained and used in the mixture designs. This was done in order to create consistent coarse aggregate volumes within mixtures. All coarse aggregate used in this study was sieved and recombined with the gradations shown in Table 3.3. Gradations were done in accordance with ASTM C136 (2006).

Table 3.4: Coarse aggregate gradation for normal CA (left) and LWCA (right)

	57/67 CA	**Structural 3/8" LWCA**
Sieve	% Passing	% Passing
1”	100%	100%
3/4”	88%	100%
1/2”	41%	100%
3/8”	23%	72%
#4	2%	1%
#8	0%	0%

3.5 Cementitious Material

The goal of internal curing is to provide his is equivalent to the volume of that lost to chemical shrinkage. In order to create mixture design and begin casting, the investigative team assumed a chemical shrinkage value of 0.064 mL/g. The chemical compositions for the cement and fly ash used in this study can be found in Table 3.4. Chemical shrinkage and the obtained values will be further discussed later in the report. The particle sizes were measured using a Coulter LS32 particle size analyzer with high reproducibility (<

1%), with methanol as a dispenser. The results for three trials of the particle size distributions for both the cement and fly ash used in this study are shown in Figure 3.2 and 3.3, respectively.

Table 3.5:Chemical analysis results of the cement and fly ash used in this study.

Analysis Results			
Chemical	**Symbol**	**Type I-II Cement**	**Class F Fly Ash**
Silicon Dioxide	SiO_2	20.0%	62.8%
Aluminum Oxide	AL_2O_3	4.7%	18.5%
Iron Oxide	FE_2O_3	3.2%	4.4%
Calcium Oxide	CaO	64.0%	5.2%
Magnesium Oxide	MgO	1.4%	0.0%
Sulfur Trioxide	SO_3	3.3%	0.6%
Loss of Ignition	LOI	2.1%	0.7%
Equivalent Alkalis	-	0.6%	0.0%

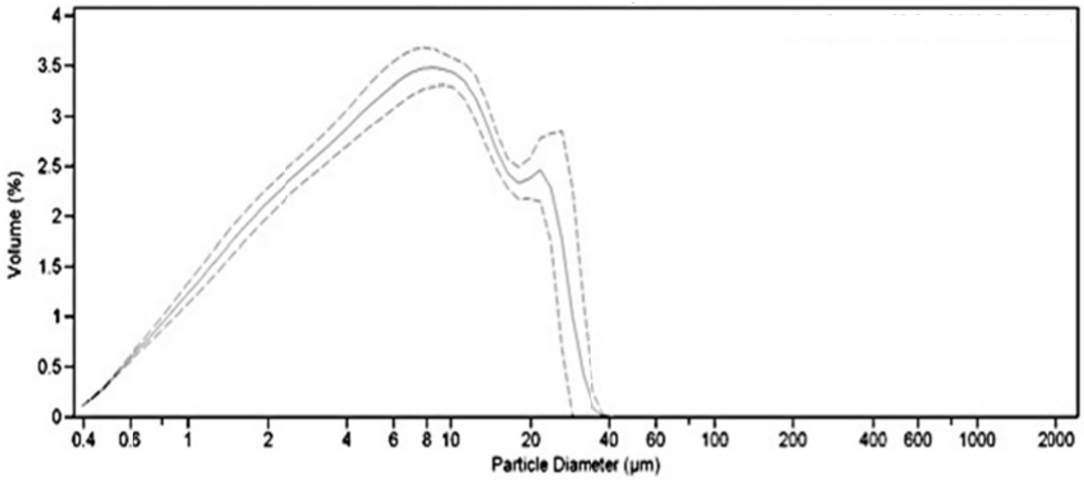


Figure 3.2: Differential pore size distribution determined by laser diffraction for the Type I-II cement used for this study.

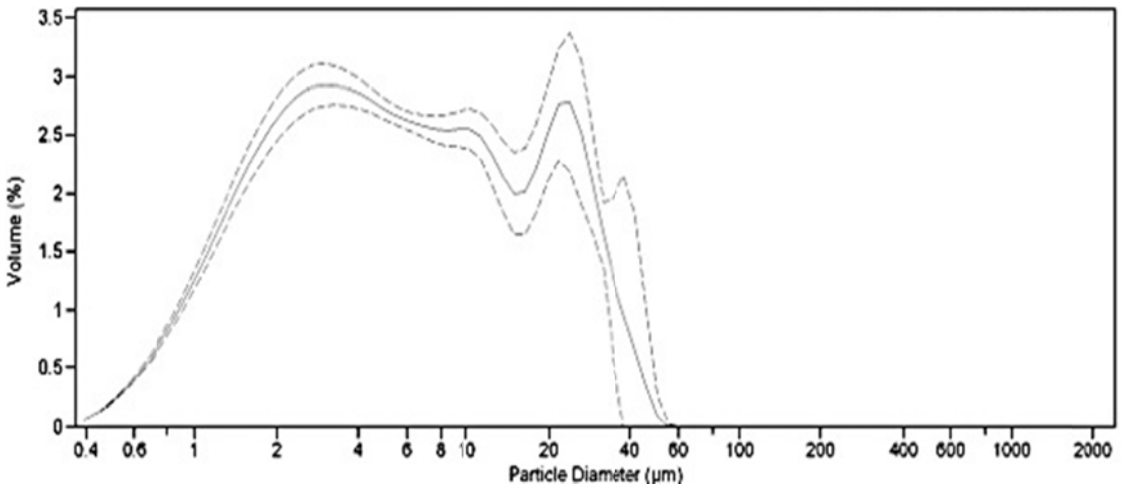


Figure 3.3: Differential pore size distribution determined by laser diffraction for Class F fly ash used for this study

CHAPTER 4. METHODS AND MATERIALS

4.1 Mixtures Evaluated

The intent of this study is to evaluate the properties of internally cured Colorado Class H and D bridge deck mixtures in comparison to the standard mixtures. This study will also demonstrate the appropriate use of internal curing through porous inclusions and how inappropriately proportioning internal curing can become problematic. The investigative team has created nine mixtures for testing in which the only variable is the amount of LWA used for internal curing and the type/ supplier of LWA used for internal curing. A description of the mixtures can be seen in Table 4.1. From this point forward in the report, the ID given in the table will be used to refer to each mixture. It had been previously mentioned that two phases of testing were performed. The first phase will be referred to as preliminary mixtures and the second phase optimized mixtures. The preliminary mixtures consist of the mixtures labeled ‘Mix 1 – Mix 5’ in Table 4.1 and the optimized mixtures labeled ‘Mix 6 – Mix9'.

4.2 Mixture Proportioning

This aim of this study is to determine the perks of internally cured concrete by closely replicating the aforementioned Colorado DOT concrete mixtures. In order to achieve replicate mixtures, the Colorado DOT Construction Specification Section 601 for Structural Concrete (Colorado Department of Transportation, 2011a) and the 2011 revision of Section 601 for Class H and HT bridge deck concrete (Colorado Department of Transportation, 2011b) were used to obtain the mixture proportions presented in this section.

Table 4.1: Description of mixtures used in this study and ID's in which they will be referred for the remainder of this report

ID	Mixture Description
Mix 1	Standard Class H Colorado Department of Transportation bridge deck mixture
Mix 2	Standard Class H Colorado Department of Transportation bridge deck mixture where a portion of the fine aggregate is replaced by TXI fine lightweight aggregate (enough lightweight aggregate is used to replace the water lost by chemical shrinkage)
Mix 3	Standard Class H Colorado Department of Transportation bridge deck mixture where a portion of the fine aggregate is replaced by TXI fine lightweight aggregate (enough lightweight aggregate is used to replace twice the water lost by chemical shrinkage)
Mix 4	Standard Class H Colorado Department of Transportation bridge deck mixture where a portion of the coarse aggregate is replaced by TXI coarse lightweight aggregate (enough lightweight aggregate is used to replace the water lost by chemical shrinkage)
Mix 5	Standard Class H Colorado Department of Transportation bridge deck mixture where all of the coarse aggregate is replaced by TXI coarse lightweight aggregate (aggregate spacing for a 2 mm moisture distribution is obtained was initially desired)*
Mix 6	Standard Class H Colorado Department of Transportation bridge deck mixture where a portion of the fine aggregate is replaced by Utelite fine lightweight aggregate (where enough lightweight aggregate is used to replace the water lost by chemical shrinkage)
Mix 7	Standard Class H Colorado Department of Transportation bridge deck mixture where a portion of the fine aggregate is replaced by Buildex fine lightweight aggregate (where enough lightweight aggregate is used to replace the water lost by chemical shrinkage)
Mix 8	Standard Class D Colorado Department of Transportation bridge deck mixture
Mix 9	Standard Class D Colorado Department of Transportation bridge deck mixture where a portion of the fine aggregate is replaced by TXI fine lightweight aggregate (where enough lightweight aggregate is used to replace the water lost by chemical shrinkage)

*See Section 2.4 for a further explanation

Concrete mixtures were prepared for Class H mixtures, standard and internally cured. The Class H concretes have a water/ cementitious material ratio (w/c) of 0.42 with a fixed cementitious material content of 570 lb/yd^3 and 20 percent replacement of fly ash, by mass. The mixtures consist of 55 percent No. 57/67 coarse aggregate by volume of total aggregate. In addition, a water reducing admixture, Glenium 3030, and an air entraining admixture, MB-AE 90, were used. The Class D mixtures, standard and internally cured, have a w/c of 0.45. All other proportions used are consistent with that of the Class H mixture. The batching quantities for both mixtures can be seen in Table 4.2.

Class H Standard Mixture

Note: Agg in SSD Condition

	Amount (kg/m^3)	Amount (lbs/yd^3)
Cement	270	456
Fly Ash	68	114
Water	142	239
FA	885	1493
CA	1091	1840

Class D Standard Mixture

Note: Agg in SSD Condition

	Amount (kg/m^3)	Amount (lbs/yd^3)
Cement	303	510
Fly Ash	76	128
Water	170	287
FA	835	1409
CA	1029	1736

Table 4.2: Batching quantities for Class H standard mixture (left) and Class D standard mixture (right)

4.3 Mixing Procedure

Unless otherwise noted, each mixture was produced conforming to the procedure presented in this section. The mixing was carried out in accordance with ASTM C192 (2007). The concrete was made using a dual action, 3.0 ft^3 capacity pan mixer. The materials were batched in an environment with a temperature of 23 ± 2 °C. The normal weight aggregates were prepared in the oven dry state. Unless otherwise noted, LWAs were prepared according to ASTM C1761 (2012), with a soaking time of 72 ± 4 hours.

The LWA for internally cured mixtures was first soaked in the water from the mixture design. Once the desired soaking time was reached, unabsorbed mixture water was decanted and set aside for mixing. In mixtures that required less water than what was able to completely cover all LWA (mixture 5), more water than prescribed by the mixture design was added for soaking and then removed in the decanting process. The fine and coarse aggregates were first combined in a “buttered” mixer, adding a portion of the batch water to control dust and ensure proper water absorption for the aggregate. Next, the cement and fly ash were added to the mixer and combined with the aggregates until a uniform distribution was achieved. The remaining batch water was slowly added and the time of water to cement contact was noted. Immediately following the addition of water, the water reducing and air-entraining admixture were slowly added directly to the concrete. The concrete was mixed for three minutes, rested for three minutes, and then mixed for an additional two minutes.

CHAPTER 5. EVALUATION OF FRESH AND MECHANICAL PROPERTIES

5.1 Introduction

The objective of this study is to investigate the performance of internally cured, high performance concrete for potential use by the Colorado DOT. In particular, this study evaluates a series of internally cured high performance concrete mixtures, as noted in Table 4.1, for the Colorado DOT that meet the specifications of a Class H and Class D concrete. The use of internal curing in high performance concrete can increase the resistance to early-age cracking and enhance durability (Bentz and Weiss, 2011).

This chapter presents the fresh and mechanical properties of the nine mixtures. The fresh properties presented consist of slump, air content from both the volumetric and pressure methods, and density for each mixture. These tests were performed by a certified ACI Grade I concrete field-testing technician. The mechanical properties consist of compressive strength and elastic modulus values at both 28 and 56 days, tested in accordance with ASTM C39 (2012a) and ASTM C469 (2010), respectively. All values of the fresh and mechanical properties presented in this chapter were of the 'large' cast in which freeze thaw and scaling specimens were made. Values of slump and air were taken in other casts to ensure consistency of the mixtures, however only values from the large (freeze-thaw) cast are presented. The test methods and casting procedures will be discussed first, followed by the results and discussions presented in a systematic order, in which the preliminary mixtures will be presented followed by the optimized mixtures for each test being discussed.

5.2 Mixing, Placing, and Curing Procedures

Materials were batched and mixed in accordance to the procedure presented in Section 4.3. For internal curing mixtures, the LWA soaked in the required mixing water (including the water required to replace chemical shrinkage) for a 72 ± 4 hour period prior to mixing. The curing methods used for each experiment will be discussed separately, where applicable, for each individual test.

5.2.1 Fresh Properties

5.2.1.1 Slump

The hydraulic-cement concrete slump in the laboratory was determined in accordance with ASTM C143 (2004). After proper mixing of constituent materials, the mixture of interest filled the dampened standard slump cone apparatus in three lifts, being rodded 25 times per lift. The cone was then removed carefully in the vertical direction in 5 ± 2 s, with caution against lateral and torsional motion. The vertical difference between the top of the mold and the displaced original center of the top surface of the specimen was measured and recorded to the nearest ¼ in.

5.2.1.2 Air Content

Since the freeze-thaw durability of internally cured mixtures is a main focus of this study, air content of the mixtures is very important. Colorado DOT Specification Section 601 (Colorado Department of Transportation, 2011a) requires an air content within the range of 5-8% for Class H and D mixtures. An air entraining admixture was used to obtain the desired air content range. An average of the volumetric air content and the pressure method air content was required to be within this range before placement of the concrete.

5.2.1.2.1 Volumetric Method

The air content determined via the volumetric method was tested in accordance with ASTM C173 (2010b). After proper mixing of constituent materials, the mixture filled the dampened, 2.0 L [0.075 ft^3] standard measuring bowl of the air meter in two lifts, being rodded 25 times per lift. After each layer the sides of the bowl were tapped approximately 10 times with a rubber mallet to close any voids left by the tamping rod and to release any large bubbles of entrapped air. The concrete was then made flush with top of the bowl using a strike off bar and the top portion of the air meter apparatus was secured. Approximately 0.5 L [1pt] of water was added followed by 1 L [2 pt] of isopropyl alcohol. Additional water was then added until the liquid level appeared at the zero marking. The liquid tight cap was then attached.

The air meter was inverted and shook in a repetitious manner for 45 s to insure the concrete has broken free and the aggregate was heard moving in the meter. It was then placed on the ground and titled at approximately 45° from the vertical position and vigorously rolled back and forth for 1 min. The apparatus was then set in an upright position for until the liquid level stabilized and the initial air content was record to the nearest 0.25%. When the initial meter reading is obtained, the rolling procedure is repeated to obtain an final meter reading. When the reading has not changed more than 0.25% of the initial reading, than this value is recorded as the final air content. All mixture followed this procedure, as no "additional requirements" per ASTM C173 (2010b) were necessary.

5.2.1.2.2 Pressure Method

The air content via the pressure method was determined in accordance with ASTM C231 (2010). After proper mixing of constituent materials, the mixture filled the dampened, 7 L [0.25 ft^3] Type B measuring bowl of the air meter in two lifts, being rodded 25 times per lift. After each layer the sides of the bowl were tapped approximately 10 times with a rubber mallet to close any voids left by the tamping rod and to release any large bubbles of entrapped air. The concrete was then made flush with top of the bowl using a strike off bar and the top portion of the air meter apparatus was secured. Once the top portion was secured, water was injected into one of the two petcocks, until it emerged from the other. The gauge was stabilized at the initial pressure line and the main pressure valve was released. Once the gauge hand stabilized, that value was recorded as the apparent air content of the sample tested. The total air content was then calculated by subtracting the aggregate correction factor, determined by ASTM C231 (2010), from the apparent air content.

5.2.1.3 Unit Weight

The unit weight of freshly mixed concrete was determined in accordance with ASTM C138/C138M (2013). The steel bowl used in the pressure test method was used in determining unit weight (see Section 5.2.1.2.2 for dimensions). The mass of the empty bowl was obtained to the nearest 0.05 kg. A freshly mixed concrete sample was placed in the dampened steel bowl in two lifts, being rodded 25 times per lift. After consolidation, the top surface was made flush with the bowl by a strike off bar. The mass of the bowl and specimen were then obtained to the nearest 0.05 kg and the unit weight calculated.

5.2.2 Mechanical Properties

5.2.2.1 Compressive Strength

The compressive strength of cylindrical concrete specimens was determined in accordance with ASTM C39 (2012a). Sets of three, 4 in diameter by 8 in tall [100 mm by 200mm], cylinders were cast to study the compressive strength of each mixture. A set was made for testing at ages of both 28 and 56 days. The cylinders were cast in two lifts, being vibrated and rodded 25 times after each lift. After one day of curing, the cylinders were demolded, sealed, and stored in a moist chamber at a temperature of 23 ± 1 °C until testing. For each day of testing, three cylinders were tested to determine the compressive strength of the mixtures. The cylinders were loaded at a rate of 35 ± 2 psi/s [0.25 ± 0.05

MPa/s] in a 700 kip [3100 kN] hydraulic compression machine, utilizing neoprene end caps when tested.

5.2.2.2 Modulus of Elasticity

The static modulus of elasticity (Young’s modulus of elasticity) was determined using a procedure similar to that in ASTM C469 (2010). Sets of two, 4 in diameter by 8 in tall [100 mm by 200mm], cylinders were cast to study the compressive strength of each mixture. A set was made for testing at ages of both 28 and 56 days. The cylinders were cast in two lifts, being vibrated and rodded 25 times after each lift. After one day of curing in their molds, the cylinders were demolded, sealed, and stored in a moist chamber at a temperature of 23 ± 1 °C until tested. Upon testing, the cylinders were fitted with a compressometer equipped with a linear variable differential transformer (LVDT) displacement transducer. The cylinders were then loaded to 40% of their ultimate strength two separate times. The resulting slope of the stress-strain curve from the second loading was taken as the static modulus of elasticity. For each day of testing, two cylinders were tested for every mixture with no cylinder being tested at more than one age.

5.3 Results and Discussions

5.3.1 Fresh Properties

This section presents the fresh properties for the mixtures evaluated in this study. The results are presented in a tabular format, in which the slump, air content, and unit weight are provided. These values are used to describe the mixtures that are to be evaluated in the following sections and to provide each mixtures properties for future reference. Air content was required to be within a range of 5-8% for Class H and D mixtures (Colorado Department of Transportation, 2011). An air entraining admixture was used, MB-AE 90 by BASF (recommend dosage of ¼ - 4 fl oz/cwt [16 – 260 mL/100 kg]), to obtain this desired air content range. The amount used will be presented in the following sections. Since slump is not specified for Class H and D mixtures by Colorado DOT Specifications, field workability was not of concern for these mixtures. A water reducing admixture, Glenium 3030 by BASF (recommend dosage for mid-range use of 3 - 6 fl oz/cwt [195 – 390 mL/100 kg]), was added to the mixtures until desirable lab workability was achieved, taking caution to avoid aggregate-paste segregation. The amount of water reducer used is also reported.

5.3.1.1 Preliminary Mixtures

The fresh properties of the preliminary mixtures can be found in the following tables. Table 5.1 presents the amount of water reducer used, slump, unit weight (γ_c), and unit weight normalized to the standard mixture (γ_{norm}). Table 5.2 presents the amount of air entrainer used, air content via volumetric method, and air content via pressure method.

Table 5.1: Values of water reducer, slump, and unit weight (γ_c) for preliminary mixtures

Mixture:	**WR (fl oz/cwt)**	**Slump (in)**	**γ_c (lb/yd^3)**	**γ_{norm} (% of stnd.)**
Mix 1: Standard Class H	6.6	1	3950	-
Mix 2: LWFA 1 x CS	8.0	1 ½	3900	99%
Mix 3: LWFA 2 x CS	10.0	2 ½	3830	97%
Mix 4: CLWA 1 x CS	10.1	3 ¼	3770	95%
Mix 5: 100% CLWA Replacement	10.0	2	3260	83%

Table 5.2:Values of air entraining admixture dosage and air content via volumetric method and pressure method for preliminary mixtures.

Mixture:	**AE (fl oz/cwt)**	**Air$_{Pres.}$ (%)**	**Air$_{Vol.}$ (%)**
Mix 1: Standard Class H	0.2	5.80%	5.25%
Mix 2: LWFA 1 x CS	0.2	5.90%	4.75%
Mix 3: LWFA 2 x CS	0.3	5.00%	5.00%
Mix 4: CLWA 1 x CS	0.4	6.20%	5.75%
Mix 5: 100% CLWA Replacement	0.4	7.00%	5.75%

As noted, slump was not of concern for these mixtures. If a higher slump is desired for field use alteration of the mixture design, as it relates to the water reducing admixture, should be adjusted. Table 5.1 shows that mixtures containing LWAs have a lower density than the standard Class H mixture, as expected. However, ‘Mix 2’ where fine LWA is used to replace water due to chemical shrinkage only has a reduction of about 1%. When the that amount of the LWA is double, as seen in ‘Mix 3’, there is only a reduction of about 3% from the standard mixture, 'Mix 1'. The maximum reduction in unit weight is 17% for a full replacement with coarse LWA.

Table 5.2 provides air contents for each mixture. Air content for 'Mix 2 – LWFA 1 x CS' was just outside of the 5-8% range for the volumetric method, however the pressure method met the desired content. Therefore, this mixture was deemed usable, as this is the approved method used most commonly in New York and Indiana IC field deck mixtures.

5.3.1.2 Optimized Mixtures

The fresh properties of the optimized mixtures can be found in the following tables. Table 5.3 presents, for each mixture, the amount of water reducer used, the slump, unit weight (γ_c), and unit weight normalized to the standard mixture (γ_{norm}). Table 5.4 presents, for each mixture, the amount of air entrainer used, air content via volumetric method, and air content via pressure method.

Table 5.3: Values of water reducer, slump, and unit weight (γ_c) for optimized mixtures

Mixture:	**WR (fl oz/cwt)**	**Slump (in)**	**γ_c (lb/yd^3)**	**γ_{norm} (% of stnd.)**
Mix 6: IC Buildex	8.0	3	3650	92%
Mix 7: IC Utelite	8.0	5 ¼	3800	96%
Mix 8: Standard Class D	2.7	6 ½	3870	-
Mix 9: IC Class D	2.7	6 ½	3750	97%

Table 5.4: Values of air entraining admixture dosage and air content via volumetric method and pressure method for optimized mixture.

Mixture:	**AE (fl oz/cwt)**	**$\text{Air}_{\text{Pres.}}$ (%)**	**$\text{Air}_{\text{Vol.}}$ (%)**
Mix 6: IC Buildex	0.3	7.9%	6.5%
Mix 7: IC Utelite	0.3	6.8%	6.8%
Mix 8: Standard Class D	0.3	6.0%	5.8%
Mix 9: IC Class D	0.2	6.1%	5.8%

5.3.2 Mechanical Properties

This section presents the mechanical properties of the mixtures evaluated in this study. The compressive strength and modulus were taken at 28 and 56 days. The 28-day tests were chosen because this is the typical age at which compressive strength is taken. The 56-day compressive strength testing is required by Colorado DOT Specification Section 600 to be 4500 psi for Class D concrete. The 56-day compressive strength testing is required by Colorado DOT Specification Section 600 to be 4500 psi for Class H concrete. The results are presented in a comparative graphical format, as well as a tabular format. The graphical format presented for the mixtures is a bar graph of compressive strength/ elastic modulus, normalized to that of the standard mixture (Class H or D, whichever is applicable). The tables provide numerical data for both tests.

5.3.2.1 Preliminary Mixtures

The normalized compressive strengths and elastic moduli of each preliminary mixture to its standard counterpart (i.e., all preliminary mixtures are normalized to ‘Mix 1 –

Standard Class H') at an age of 28 and 56 days are shown in Figure 5.1 and Figure 5.2, respectively. Table 5.5 and 5.6 provides numerical data for compressive strength and elastic modulus (and the corresponding standard deviations) rounded to the nearest hundred psi and ksi, respectively, at 28 and 56 days. The reported values are an average of three cylinders for compressive strength and two cylinders for elastic modulus (a dash in the standard deviation column indicates that only one test for modulus returned valid results).

All preliminary mixtures well exceeded the 4,500 psi compressive strength at 56 days, required per Colorado DOT Specifications (in fact all five mixtures exceeded this at 28 days). The first trend that can be noticed is the relative performance of the IC systems. The IC mixtures (with the exception of Mix 5) had a higher compressive strength than the standard mixture. With 'Mix 5' being a 100% LWCA, it was expected that this mixture would have a slight decrease in compressive strength. The increase in compressive strength that was observed in many of the IC mixtures can be attributed to the increased hydration caused through internal curing. These conclusions coincide with what Golias et al. (Golias et al., 2012) have shown; that compressive strength of internally cured mixtures shows an increase compared to plain mixtures when sealed (as is the case for out mixtures), or drying type conditions are encountered in the curing process. This is most common to what will take place in the field. These benefits of IC do not hold true for standard samples, which are water cured, as hydration is able to continue in the plain system.

Internally cured mixtures using LWA show a reduction in the modulus of elasticity. Mixture 4 shows very similar properties to mixture 1 for elastic modulus, as only a small portion of NWA was replaced with LWA. Mixture 5 has the greatest reduction in modulus of 29% and 37% and 28 and 56 days, respectively. This reduction in modulus can be attributed the addition of porous LWA material into the system, which reduced the overall stiffness.

A decreased modulus in IC mixtures, while reducing the overall stiffness of the concrete, can actually be beneficial in reducing shrinkage cracking. The interface between NWA and paste can be an epicenter of crack formation. This is due to stress buildup from the large differences in stiffness between the NWA and paste. The NWA acts in restraint to movement of paste. When NWA particles are substituted by LWA particles, the change in stiffness, or degree of restraint, at the interface of the paste is reduced, resulting in less stress buildup and ultimately decreased cracking potential. This is consistent with work done by Raoufi using finite element modeling to examine stress development (Raoufi et al., 2011).

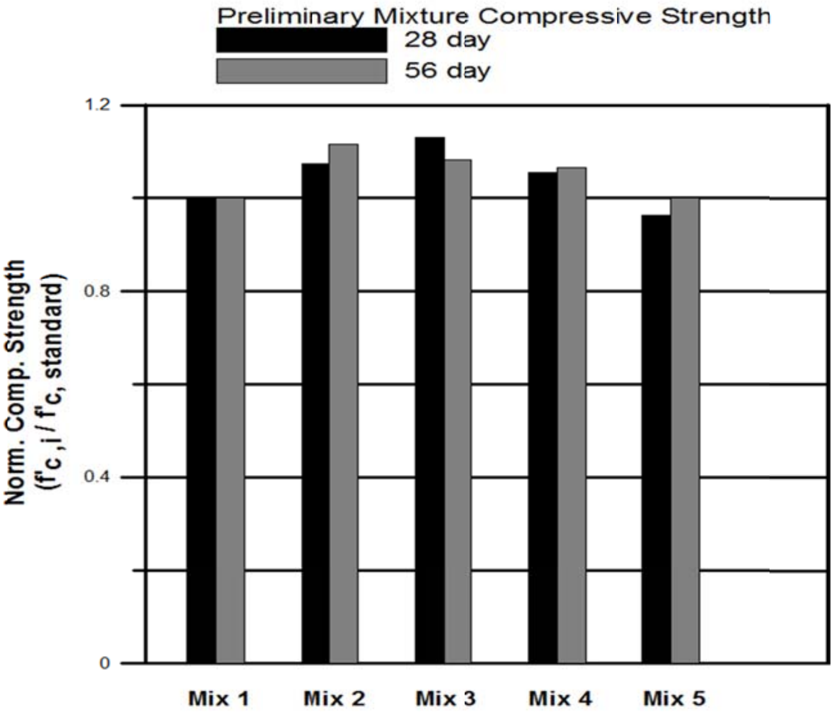


Figure 5.1: Preliminary mixtures compressive strength, normalized to standard mixture.

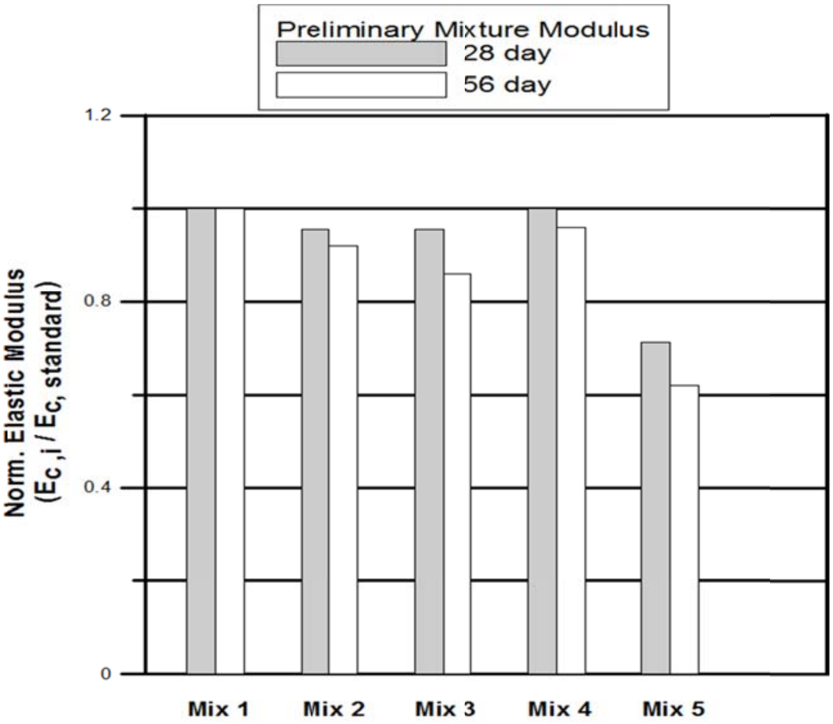


Figure 5.2: Preliminary mixtures modulus of elasticity, normalized to standard mixture.

Table 5.5: Values of compressive strength (f'$_c$) and standard deviation (STDEV) preliminary mixtures at 28 and 56 days.

Mixture:	**f'$_c$ - 28 day (psi)**	**STDEV (psi)**	**f'$_c$ - 56 day (psi)**	**STDEV (psi)**
Mix 1: Standard Class H	5400	140	6100	482
Mix 2: LWFA 1 x CS	5800	20	6800	374
Mix 3: LWFA 2 x CS	6100	88	6600	382
Mix 4: CLWA 1 x CS	5700	316	6500	303
Mix 5: 100% CLWA Replacement	5200	128	6100	146

Table 5.6: Values of Young's elastic modulus (E$_c$) and standard deviation (STDEV) preliminary mixtures at 28 and 56 days.

Mixture:	**E$_c$ - 28 day (ksi)**	**STDEV (ksi)**	**E$_c$ - 56 day (ksi)**	**STDEV (ksi)**
Mix 1: Standard Class H	4500	164	5000	-
Mix 2: LWFA 1 x CS	4300	12	4600	65
Mix 3: LWFA 2 x CS	4300	64	4300	-
Mix 4: CLWA 1 x CS	4500	-	4800	-
Mix 5: 100% CLWA Replacement	3200	80	3100	33

5.3.2.2 Optimized Mixtures

The normalized compressive strengths and elastic moduli of each optimized mixture to its standard counterpart (Mix 6 and Mix 7 are normalized to 'Mix 1 – Standard Class H' and Mix 9 is normalized to 'Mix 8 – Standard Class H') at an age of 28 and 56 days are shown in Figure 5.3 and Figure 5.4, respectively. Table 5.7 and 5.8 provides numerical data for compressive strength and elastic modulus (and the corresponding standard deviations) rounded to the nearest hundred psi and ksi, respectively, at 28 and 56 days.

Mix 1 – Standard Class H is shown on the plots as a reference. The reported values are an average of three cylinders for compressive strength and two cylinders for elastic modulus.

The internally cured Class H optimized mixtures, Mix 6 and Mix 7, well exceeded the 4,500 psi compressive strength requirement, at 56-days, required by Colorado DOT specifications for Class H concrete. The Class D requirements specify that a 4,500 psi compressive strength must be met at a 28-day time period. The standard Class D mixture, Mix 8, did not meet the meet this strength requirement. It should be noted that this was the standard Class D mixture and that the IC mixture, Mix 9, exceeded the 4,500 psi requirement. Unlike the other IC Class H mixtures (excluding Mix 5), Mix 7’s compressive strength was less than that of Standard Class H for both 28 and 56 days. This could be due to LWFA being a more porous material. Mix 9, internally cured Class D mixture, far exceeded the standard Class D mixture in compression for both 28 and 56 days. Similar to the preliminary mixtures, the internally cured optimized mixture show a reduction in the modulus of elasticity.

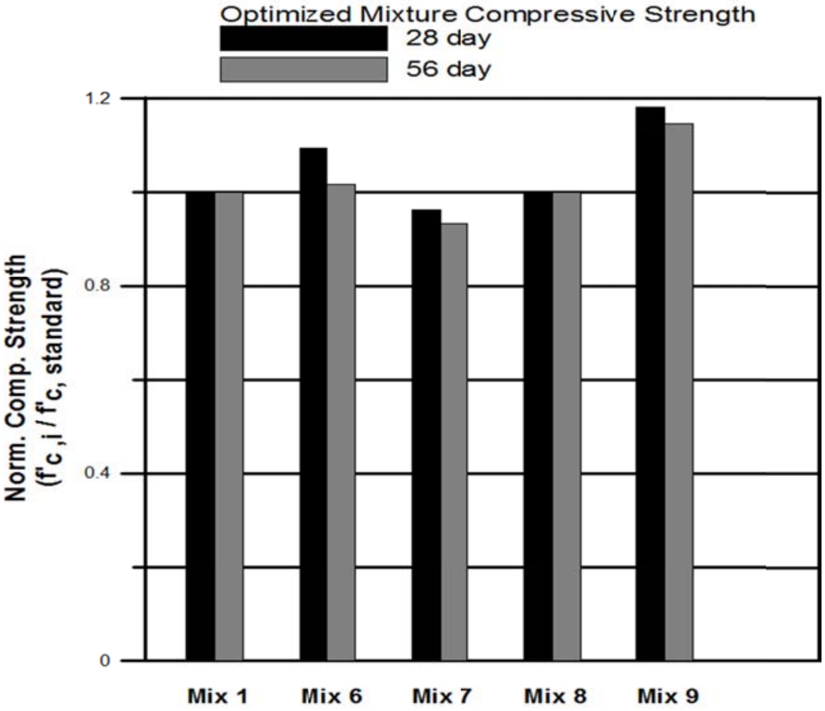


Figure 5.3: Optimized mixtures compressive strength, normalized to standard mixture.

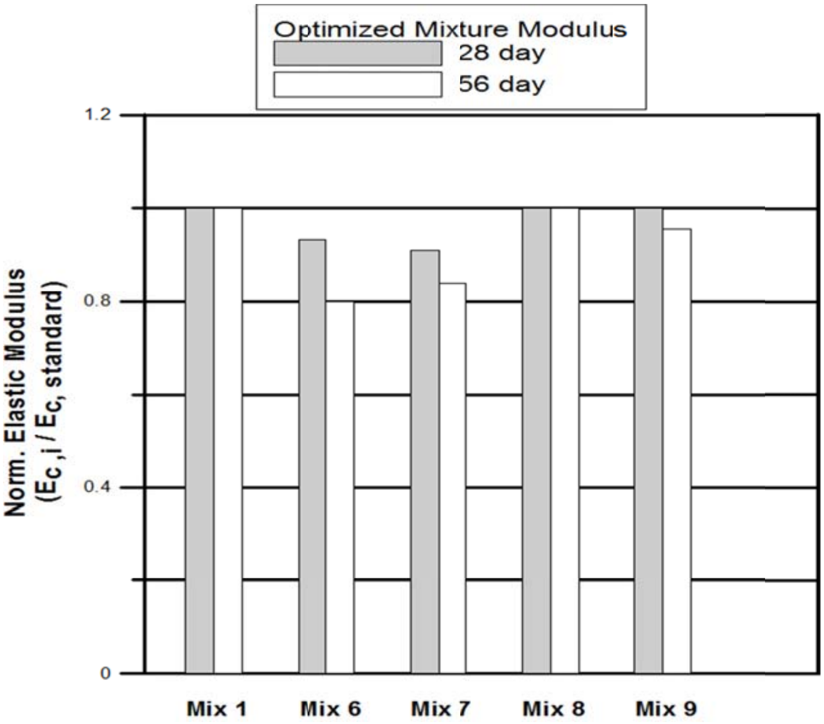


Figure 5.4: Preliminary mixtures modulus of elasticity, normalized to standard mixture.

Table 5.7: Values of compressive strength (f'_c) and standard deviation (STDEV) optimized mixtures at 28 and 56 days.

Mixture:	**f'_c - 28 day (psi)**	**STDEV (psi)**	**f'_c - 56 day (psi)**	**STDEV (psi)**
Mix 6: IC Buildex	5900	22	6200	77
Mix 7: IC Utelite	5200	219	5700	243
Mix 8: Standard Class D	4400	131	4800	45
Mix 9: IC Class D	5200	222	5500	45

Table 5.8: Values of Young's elastic modulus (E_c) and standard deviation (STDEV) optimized mixtures at 28 and 56 days.

Mixture:	**E_c - 28 day (ksi)**	**STDEV (ksi)**	**E_c - 56 day (ksi)**	**STDEV (ksi)**
Mix 6: IC Buildex	4200	13	4000	20
Mix 7: IC Utelite	4100	76	4200	108
Mix 8: Standard Class D	4000	112	4400	-
Mix 9: IC Class D	4000	18	4200	68

5.4 Summary and Conclusions

This chapter investigated the fresh and mechanical properties of both standard and internally cured Colorado DOT Class H and D mixtures. The fresh properties presented consist of slump, air content from both the volumetric and pressure methods, and density for each of the nine mixtures. These tests were performed by a certified ACI Grade I concrete field-testing technician. The mechanical properties consist of compressive strength and elastic modulus values at both 28 and 56 days. All values of fresh and mechanical properties presented in this chapter were of the ‘large’ cast in which freeze thaw and scaling specimens were made. Results from this chapter can be summarized as follows:

- Slump was not of concern for these mixtures. If a higher slump is desired for field use the amount water reducing admixture should be adjusted.
- Mixtures containing LWAs (i.e., IC mixtures) have a lower density than the standard mixtures, as expected.
- An air entraining admixture was used to obtain the desired air content per Colorado DOT Specifications for both standard and IC mixtures. The pressure method is the preferred method for obtaining air content since it is easier for field use. However, the volumetric method provides a somewhat consistent and comparable value.
- In compression, the IC mixtures for most cases performed better than the standard mixture. The increase in compressive strength is attributed to the increased hydration caused through internal curing. These findings are consistent with work done by Golias (Golias et al., 2012).

- The IC mixtures were all above the values specified by Colorado DOT specification for Class H and Class D mixtures of 4,500 psi at 28 and 56 days, respectively.
- All IC mixtures showed a reduction in the modulus of elasticity, which is attributed to adding a material that has reduced stiffness, i.e., LWA.
- The reduction in modulus will actually benefit mixtures in reducing shrinkage cracking, as the modulus at the interface of the aggregate and paste are more similar and do not create a large restraint, which would consequently generate large stresses.

CHAPTER 6. EVALUATION OF CYCLIC FREEZING AND THAWING BEHAVIOR

6.1 Introduction

The objective of this study is to investigate the performance of internally cured, high performance concrete for potential use by the Colorado DOT. In particular, this study evaluates a series of internally cured high performance concrete mixtures, as noted in Table 4.1, for the Colorado DOT that meet the specifications of a Class H and Class D concrete. The use of internal curing in high performance concrete can increase the resistance to early-age cracking and enhance durability (Bentz and Weiss, 2011).

This chapter presents the results of the nine mixtures with respect to their resistance to scaling and rapid freeze-thaw durability. The test methods and casting procedures will be discussed first, followed by the results and discussions presented in a systematic order, in which the preliminary mixtures will be presented, followed by the optimized mixtures for each test being discussed.

6.2 Mixing, Placing, and Curing Procedures

Materials were batched and mixed in accordance to the procedure presented in Section 4.3. For internal curing mixtures, the LWA was soaked in the required mixing water (including the water required to replace chemical shrinkage) for a 72 ± 4 hour period prior to mixing. The curing methods used for each experiment will be discussed individually where applicable, as curing methods used for a particular test may not be a desirable method for another. Fresh properties of the concrete were taken and can be found in Tables 5.1-5.4. Special attention was taken to ensure that the air content of each mixture was within the range of 5-8%, as prescribed by Colorado DOT Specification Section 601 (Colorado Department of Transportation, 2011a).

6.2.1 Rapid Freezing and Thawing

The rapid freezing and thawing durability of each mixture was determined in accordance with ASTM C666 (2003, reapproved 2008). Sets of three 4 in wide by 3 in tall by 16 in long samples were cast for each mixture to study the resistance to rapid freezing and thawing. The specimens were cast in two lifts, being vibrated and rodded 25 times after each lift, and trowel finished on the top surface. After a 24 ± 2 hour period the specimens were removed from the molds, bag sealed, and placed in a moist chamber at 23 ± 1°C [73.5 ± 1.5 °F] for a 14-day curing period.

After the curing period, the specimens were removed from the bags and for consistency in testing, were brought to the target internal thaw temperature, within -1°C and +2°C [-2°F and 4°F]. At this point the concrete specimens masses were determined and they were tested for transverse frequency. All transverse frequency testing was performed in accordance with ASTM C215 (2008). After initial measurement were determined, specimens were placed in a pan with water, such that all faces were completely surrounded by not less than 1/32 in. [1 mm] nor more than 1⁄8 in. [3 mm] of water at all times while it is being subjected to freezing-and-thawing cycles. The pans containing water and the concrete specimens were then placed in a chamber that underwent freeze-thaw cycling in which consist of alternately lowering the temperature of the specimens from 40 to 0 °F [4 to -18 °C] and raising it from 0 to 40 °F [-18 to 4 °C] in 4 ½ ± ½ hour. Specimens were removed at the desired thaw temperature and tested approximately every 36 cycles, until a total of 300 cycles or until its relative dynamic modulus of elasticity reached 60% of the initial modulus, whichever occurred first.

6.2.2 Scaling Resistance to Deicing Chemicals

The scaling resistance of each mixtures horizontal concrete surface exposed to freezing and thawing in the presence of deicing chemicals was determined in accordance with ASTM C672 (2003) as well as Ontario Ministry of Transportation's (MTO's) scaling test (MTO LS-412). The intent for using a combination of these standards was to evaluate the surface resistance of the mixtures through both qualitative and quantitative examination. Sets of three 7 ½ in wide by 3 in tall by 10 in samples were cast for each mixture to study the resistance to rapid freezing and thawing. The specimens were cast in two lifts, being vibrated and rodded 25 times after each lift. The samples were finished using a steel trowel by the same person with the intent of maintaining consistency for the finished surface. After a 24 ± 2 hour period the specimens were removed from the molds, bag sealed, and placed in a moist chamber at 23 ± 1°C [73.5 ± 1.5 °F] for a 14-day "moist storage" curing period. The specimens were then removed from the bags and placed in a chamber at 50 ± 1 %RH and 23 ± 1°C for a 14-day "air storage" curing period.

After the curing period, a dike made of Styrofoam and secured by rubber silicone, is placed along the perimeter of the top surface of each specimen. The dike is to hold approximately 6 mm [1/4 in.] of a solution containing 4 g of anhydrous calcium chloride to each 100 mL of water. The specimens are then placed in an environmental chamber in which the temperature cycles from −18 ± 3°C [0 ± 5°F] within 17 hours to 23 ± 2.0°C [73.5 ± 3.5°F] and 50 ± 1 %RH within 7 hours. This was repeated for a total of 50 cycles, while qualitative and quantitative examination was performed after 5, 10, 15, 25, and 50 cycles. Qualitative examination consisted of a visual rating on a scale of 0 – 5, where 0 indicates no scaling and 5 indicates severe scaling. A plus/ minus rating was also used to help further separate differences in scaling. For example a ‘2+’ indicates less scaling than a ‘2’ while a ‘2-‘ indicates more scaling. Photographs were also taken each time the samples were removed from the chamber for examination. Since the visual ratings desired by ASTM C672 (2003) are not particularly descriptive and leave much room operator variability and bias, an additional quantitative examination was performed to better assess differences in mixture scaling. MTO LS-412 states that “After each 5 cycles, remove the salt solution together with all the flaked off concrete from the surface and place into a watertight contain…washing the surface of the specimen… strained through a filter and the residue dried out in an oven at 105 °C to a constant mass condition.” (MTO LS-412 R17). For each of the specimens, the top surface was flushed and scaled materials was carefully removed and from the specimen. The scaled material was then measured in terms of oven dry mass. At the conclusion of each examination fresh solution was added to the top surface and the specimens were placed back in the chamber.

6.3 Results and Discussions

6.3.1 Rapid Freezing and Thawing

Before presenting the results, it should be again noted that this testing method is performed using 14-day bag sealed curing method. The beam specimens go directly from a sealed condition into the testing chamber, never experiencing a drying period. While it is possible to replicate this condition in the field, it is unlikely and results should be viewed as a "worst case scenario" situation. This is done to clearly identify which mixtures perform poorly in freeze-thaw conditions.

6.3.1.1 Preliminary Mixtures

The results of the preliminary mixtures from rapid freezing and thawing can be seen in the figures and table below. Figure 6.1 shows each mixtures relative dynamic modulus (or durability) and Figure 6.2 the mass change as a function of the number of cycles. The data shown in the plots is a summary of an average of three beam specimens. 'Mix 5 – 100% LWCA Replacement' is only shown to 195 cycles due to specimen failure at that point. Although the line presented does not cross the failure limit at 195 cycles, a specimen was unable to be tested past this point.

Table 6.1 summarizes the durability factors (calculated from relative dynamic modulus and a ratio of the number of cycles reached to the specified number of cycles in which exposure is to be terminated) of each beam specimen and shows an average durability factor for each mixture as well as a summary of the mass change. The line at 60%

relative dynamic modulus indicates the failure limit as specified by ASTM C666 (2003, reapproved 2008).

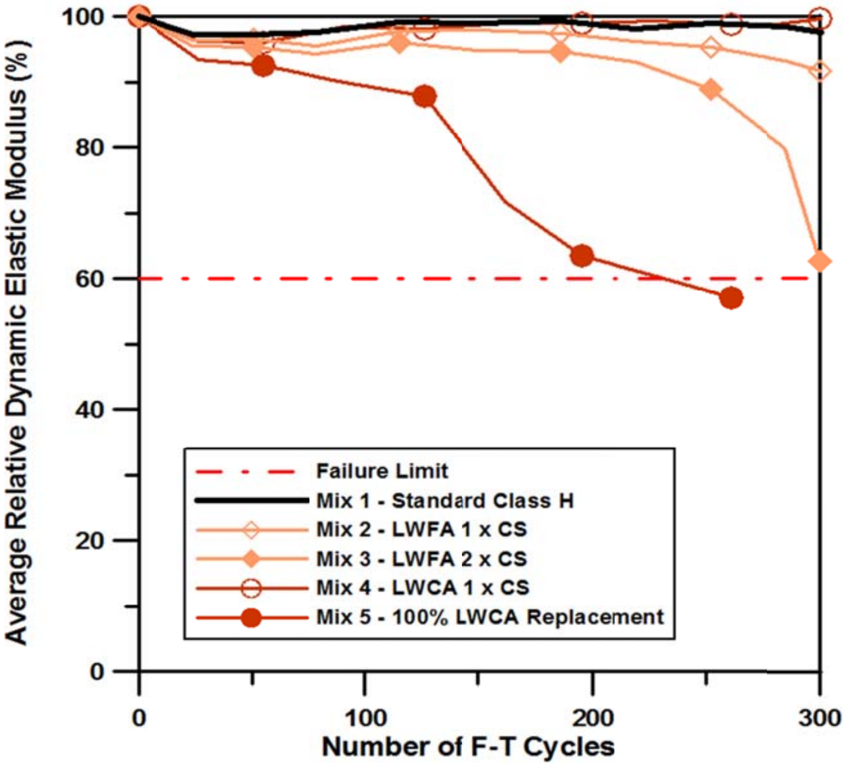


Figure 6.1: Plot of Mixtures 1-5 average relative dynamic modulus by ASTM C666 (2003, reapproved 2008) rapid freezing and thawing.

From the presented data, it is clear that "excessively" internal cured mixtures, as is the case for 'Mix 3 – LWFA 2 x CS' and 'Mix 5 – 100% LWCA Replacement', have the potential to not perform well in freeze-thaw environments. It should be noted that from Table 6.1 a beam failed for both 'Mix 3 – LWFA 2 x CS' and 'Mix 5 – 100% LWCA Replacement', where a durability factor of less than 60% in considered failure. Also, Figure 6.1 shows that 'Mix 3 – LWFA 2 x CS' approaches failure (and would have likely

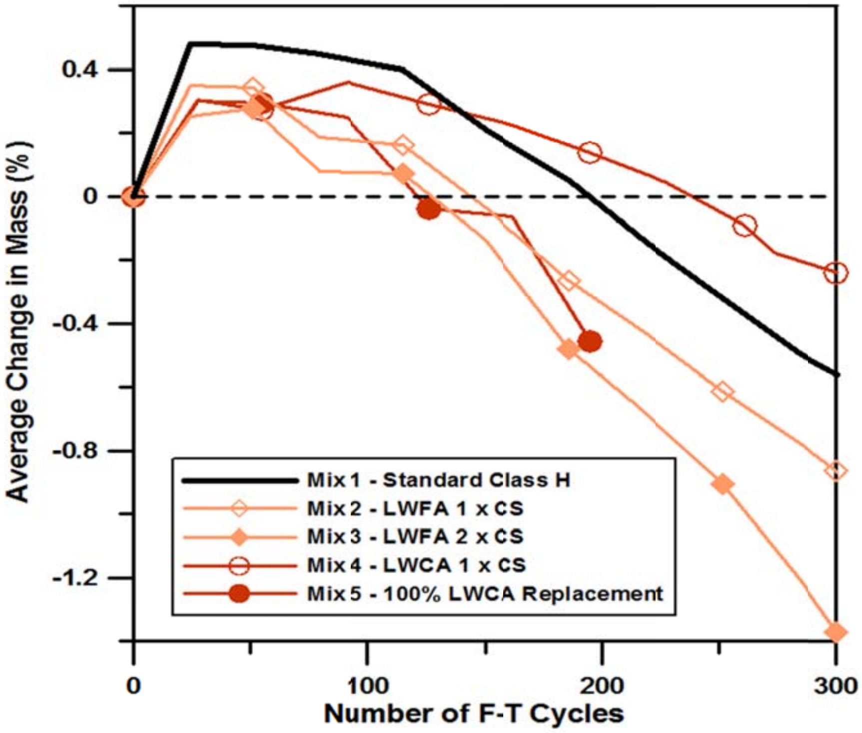
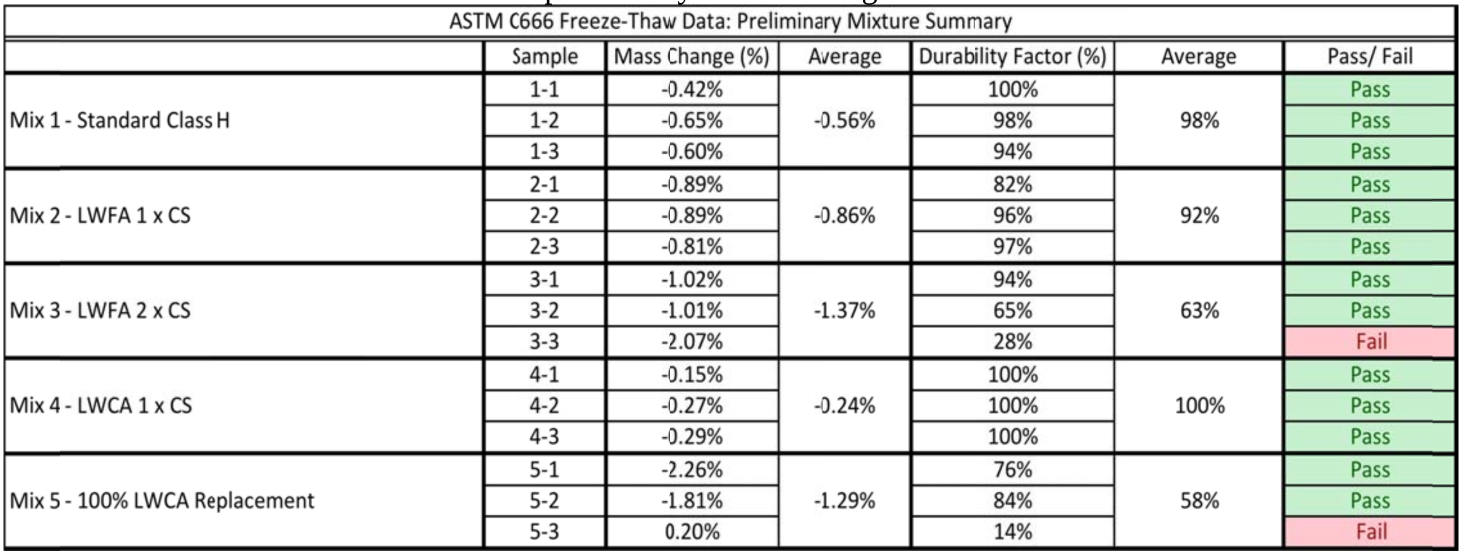


Figure 6.2: Plot of Mixtures 1-5 average mass change by ASTM C666 (2003, reapproved 2008) rapid freezing and thawing.

Table 6.1: Summary of ASTM C666 (2003, reapproved 2008) rapid freezing and thawing data for preliminary mixture designs.



ASTM C666 Freeze-Thaw Data: Preliminary Mixture Summary

	Sample	Mass Change (%)	Average	Durability Factor (%)	Average	Pass/ Fail
Mix 1 - Standard Class H	1-1	-0.42%	-0.56%	100%	98%	Pass
	1-2	-0.65%		98%		Pass
	1-3	-0.60%		94%		Pass
Mix 2 - LWFA 1 x CS	2-1	-0.89%	-0.86%	82%	92%	Pass
	2-2	-0.89%		96%		Pass
	2-3	-0.81%		97%		Pass
Mix 3 - LWFA 2 x CS	3-1	-1.02%	-1.37%	94%	63%	Pass
	3-2	-1.01%		65%		Pass
	3-3	-2.07%		28%		Fail
Mix 4 - LWCA 1 x CS	4-1	-0.15%	-0.24%	100%	100%	Pass
	4-2	-0.27%		100%		Pass
	4-3	-0.29%		100%		Pass
Mix 5 - 100% LWCA Replacement	5-1	-2.26%	-1.29%	76%	58%	Pass
	5-2	-1.81%		84%		Pass
	5-3	0.20%		14%		Fail

failed if the test were extended past 300 cycles). It can also be seen in the figure that 'Mix 5 – 100% LWCA Replacement' fails with about 100 cycles remaining.

Failures in mixtures where more is provided water than what is necessary to replace the water lost due to chemical shrinkage is likely due to excess, unused, water present in the system. The concrete matrix will draw water the LWAs due to chemical shrinkage. When excessive chemical shrinkage water is used, the additional water remains trapped in the system, which can become very problematic when introduced to freezing and thawing.

Concretes that perform well in freeze-thaw environments have enough empty air voids present to accommodate the expansion from freezing water in the pores. Water can expand by approximately 9% in volume (Powers, 1945) as freezing occurs. If a sufficient amount of air voids are present, and connected, in the system to account for this expansion in volume, damage become unlikely. If there is not enough empty pore space in the system, or similarly an overabundance of water, the water starts to expand with nowhere to go. This creates stress buildup inside the materials and will create internal micro cracking, which build up and damage the integrity of the concrete. (Tanesi and Meininger, 2007).

However, if the correct amount of water to replace that which is lost in chemical shrinkage is supplied, as in the case for 'Mix 2 – LWFA 1 x CS' the results are very similar to that of the standard mixture, ‘Mix 1 – Standard Class H’. The mixture labeled ‘Mix 4 – LWCA 1 x CS’ is not included in the previous statement because it has been shown earlier in this report that the LWA particles are spaced too far apart to be the most effective IC mixture. This mixture therefore performs very similarly to the reference mixture, ‘Mix 1 – Standard Class H’ in freezing and thawing.

6.3.1.2 Optimized Mixtures

The results of the optimized mixtures from rapid freezing and thawing can be seen in the figures and table below. Figure 6.3 shows each mixtures relative dynamic modulus (or durability) and Figure 6.4 the mass change as a function of the number of cycles. The data shown in the plots is a summary of an average of three beam specimens, except for ‘Mix 9 – IC Class D’ which is an average of two beam specimens due to a damaged beam prior to testing. ‘Mix 1 – Standard Class H’ has also been plotted as a reference for ‘Mix 6 – IC Buildex’ and ‘Mix 7 – IC Utelite’, which are also Class H mixtures. Table 6.2 summarizes the durability factors (calculated from relative dynamic modulus and a ratio of the number of cycles reached) of each beam specimen and shows an average durability factor for each mixture as well as a summary of the mass change. The line at 60% relative dynamic modulus indicates the failure limit as specified by ASTM C666 (2003, reapproved 2008).

From the presented data it can be seen that all beam specimens performed well in the rapid freeze thaw test. Both additional LWAs, ‘Mix 6 – IC Buildex’ and ‘Mix 7 – IC

Utelite’, have showed no issues in a freeze-thaw environment. The Class D mixture, standard and internally cured, are presented as ‘Mix 8 – Standard Class D’ and ‘Mix 9 – IC Class D’. Both mixtures have a w/c of 0.45, which is higher than the Class H mixtures of 0.42. It is noticed that the internally cured Class D mixture performed slightly worse than the standard Class D. However, with a durability factor of 96%, this is not of concern.

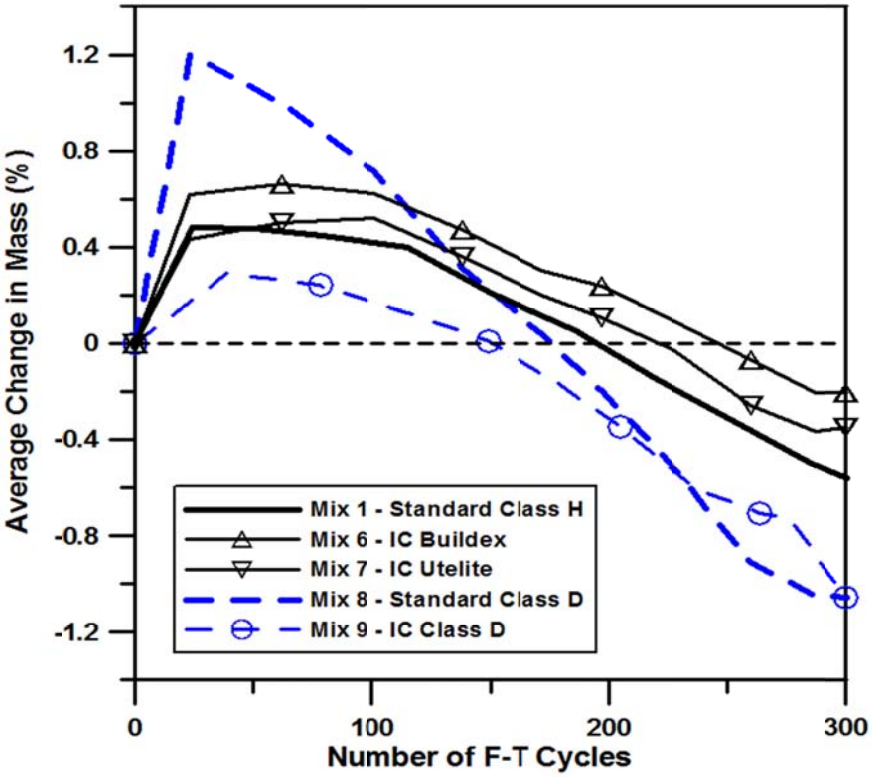


Figure 6.3: Plot of Mixtures 6-9 average relative dynamic modulus by ASTM C666 (2003, reapproved 2008) rapid freezing and thawing.

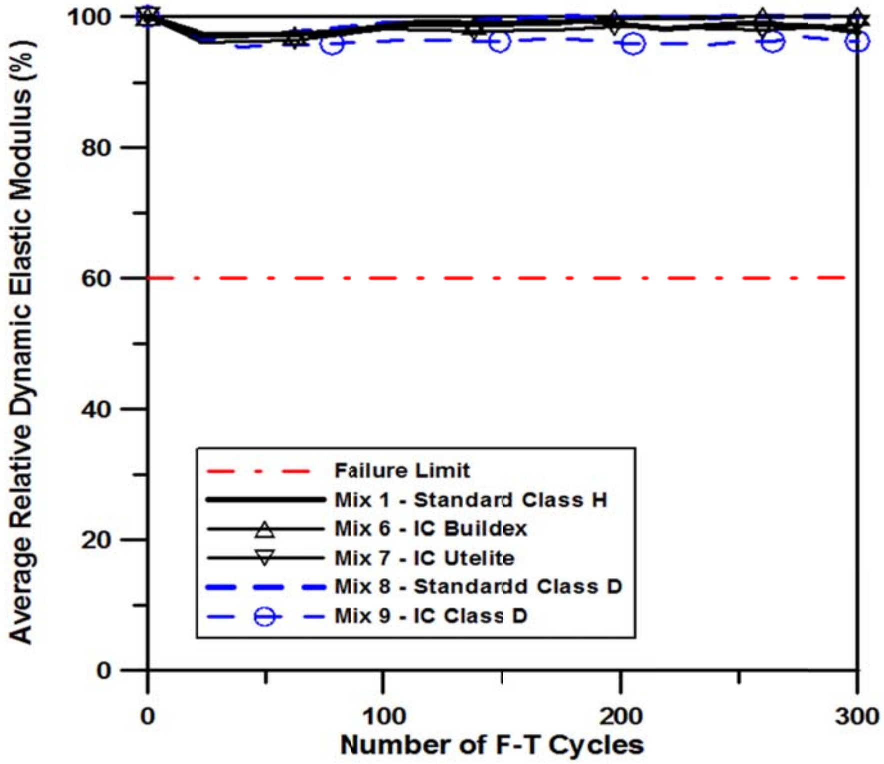
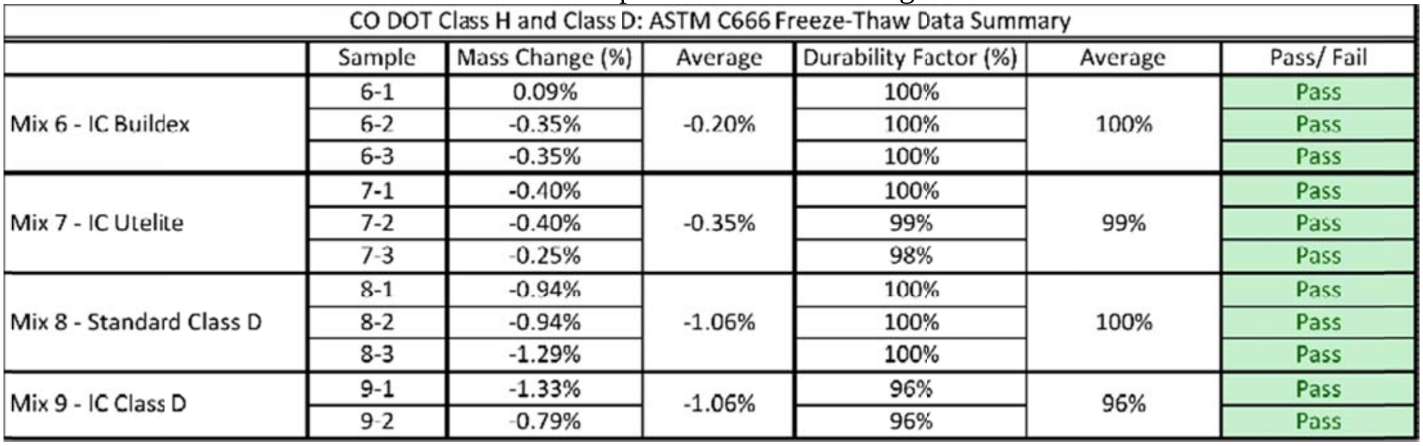


Figure 6.4: Plot of Mixtures 6-9 average mass change by ASTM C666 (2003, reapproved 2008) rapid freezing and thawing. Mixture 1 is plotted again for reference.

Table 6.2: Summary of ASTM C666 (2003, reapproved 2008) rapid freezing and thawing data for optimized mixture designs.



CO DOT Class H and Class D: ASTM C666 Freeze-Thaw Data Summary						
	Sample	Mass Change (%)	Average	Durability Factor (%)	Average	Pass/ Fail
Mix 6 - IC Buildex	6-1	0.09%	-0.20%	100%	100%	Pass
	6-2	-0.35%		100%		Pass
	6-3	-0.35%		100%		Pass
Mix 7 - IC Utelite	7-1	-0.40%	-0.35%	100%	99%	Pass
	7-2	-0.40%		99%		Pass
	7-3	-0.25%		98%		Pass
Mix 8 - Standard Class D	8-1	-0.94%	-1.06%	100%	100%	Pass
	8-2	-0.94%		100%		Pass
	8-3	-1.29%		100%		Pass
Mix 9 - IC Class D	9-1	-1.33%	-1.06%	96%	96%	Pass
	9-2	-0.79%		96%		Pass

6.3.2 Scaling Resistance to Deicing Chemicals

6.3.2.1 Preliminary Mixtures

The results of the preliminary mixtures from scaling resistance can be seen in the following figure and table. Figure 6.5 shows a plot of the preliminary mixtures quantitative results for scaling, normalized to the surface area exposed to deicing chemicals. This plot is the cumulative amount of residue lost during the 50 cycles of exposure. The results in this plot show an average of the three specimens tested. Table 6.3 summarizes the cumulative residue lost of each specimen, the visual rating, and averages of both for each mixture at 50 cycles.

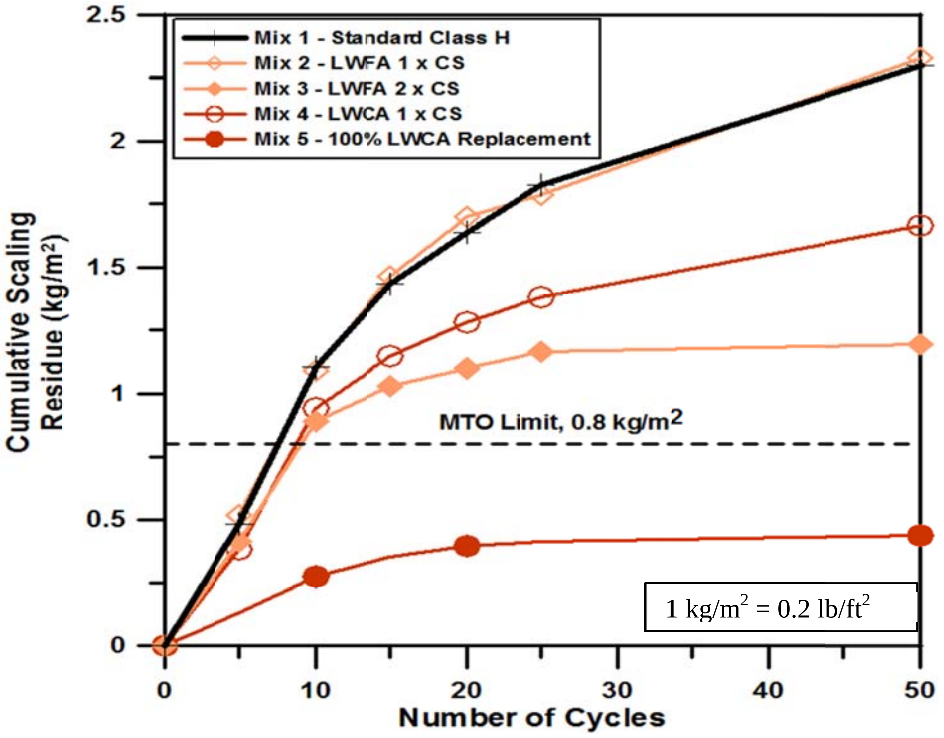
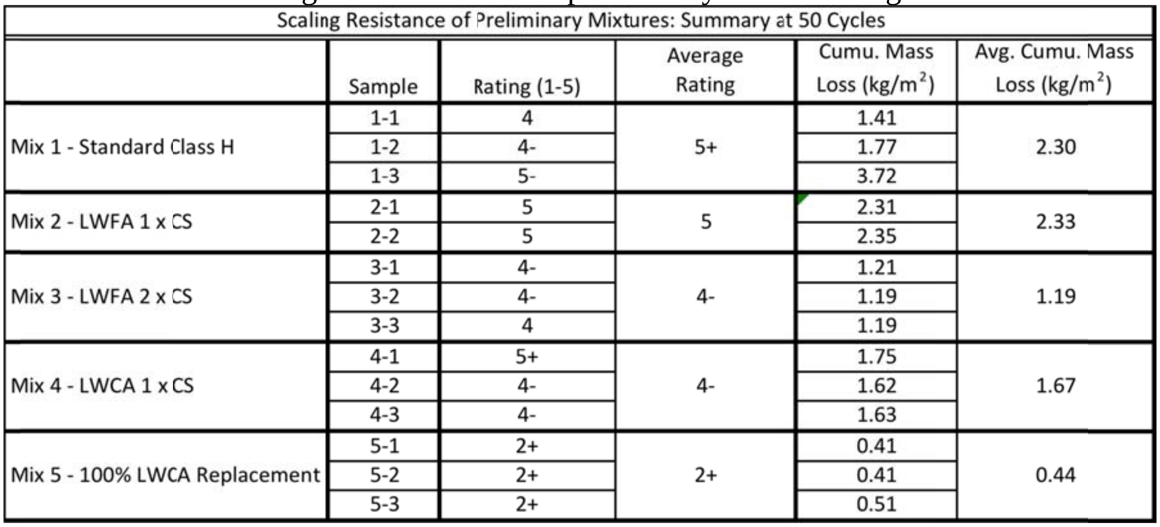


Figure 6.5: Plot of Mixtures 1-5 average cumulative scaling by ASTM C672 (2003) and MTO LS-412 scaling resistance to deicing chemicals.

Table 6.3: Summary of ASTM C672 (2003) and MTO LS-412 scaling resistance to deicing chemicals data for preliminary mixture designs.



Scaling Resistance of Preliminary Mixtures: Summary at 50 Cycles

	Sample	Rating (1-5)	Average Rating	Cumu. Mass Loss (kg/m^2)	Avg. Cumu. Mass Loss (kg/m^2)
Mix 1 - Standard Class H	1-1	4	5+	1.41	2.30
	1-2	4-		1.77	
	1-3	5-		3.72	
Mix 2 - LWFA 1 x CS	2-1	5	5	2.31	2.33
	2-2	5		2.35	
Mix 3 - LWFA 2 x CS	3-1	4-	4-	1.21	1.19
	3-2	4-		1.19	
	3-3	4		1.19	
Mix 4 - LWCA 1 x CS	4-1	5+	4-	1.75	1.67
	4-2	4-		1.62	
	4-3	4-		1.63	
Mix 5 - 100% LWCA Replacement	5-1	2+	2+	0.41	0.44
	5-2	2+		0.41	
	5-3	2+		0.51	

1 kg/m^2 = 0.2 lb/ft^2

The dashed line shown at 0.8 kg/m^2 indicates the limit of scaling suggested by MTO. It should be noted that this limit is the MTO limit, which is set for a similar scaling test using 3% NaCl, not 4% CaCl. This limit does not intend to provide a distinct failure limit for out mixture, it is simply there to provide a reference for scaling durable concrete. ASTM C672 (2003) has been shown to be inconsistent from test to test and to largely depend on how the samples were finished. It is interesting to note that the MTO scaling test concluded inconsistencies as high as 59% in slag mixtures from duplicate samples (Bleszynski et al., 2002). With that being said, the main point to take from these results is that the IC mixtures do not perform any worse than ‘Mix 1 – Standard Class H’. The investigative team believes the reason ‘Mix 5 – 100% CLWA Replacement’ performs well in the scaling test is due in part to altering the thermal properties of the concrete with large replacements of LWA, which is outside of the scope of this project.

6.3.2.2 Optimized Mixtures

The results of the optimized mixtures from scaling resistance can be seen in the following figure and table. Figure 6.6 shows a plot of each optimized mixtures quantitative results for scaling, normalized to the surface area exposed to deicing chemicals. This plot is the cumulative amount of residue lost during the 50 cycles of exposure. The results in this plot show an average of the three specimens tested. Table 6.4 summarizes the cumulative residue lost of each specimen, the visual rating, and averages of both for each mixture at 50 cycles.

The dashed line shown at 0.8 kg/m^2 indicates the limit of scaling suggested by to MTO. It should be noted that this limit is the MTO limit, which is set for a similar scaling test using 3% NaCl, not 4% CaCl. This limit does not intend to provide a distinct failure limit for out mixture, it is simply there to provide a reference for scaling durable concrete. ASTM C672 (2003) has been shown to be inconsistent from test to test and to largely depend on how the samples were finished. If finishing is not perfectly consistent from sample to sample, the microstructure will considerably weaken, even if the concrete is properly air entrained. It is interesting to note that the MTO scaling test concluded perform any worse than ‘Mix 1 – Standard Class H’. However, the internally cured Class D mixture, ‘Mix 9 – IC Class’, does perform worse than the standard Class D mixture, ‘Mix 8 – Standard Class D’. This could be due to finishing, or IC mixture could possibly not work well in scaling with a higher w/c. More investigation may need to be performed to determine if w/c has an effect on scaling with internally cured mixtures.

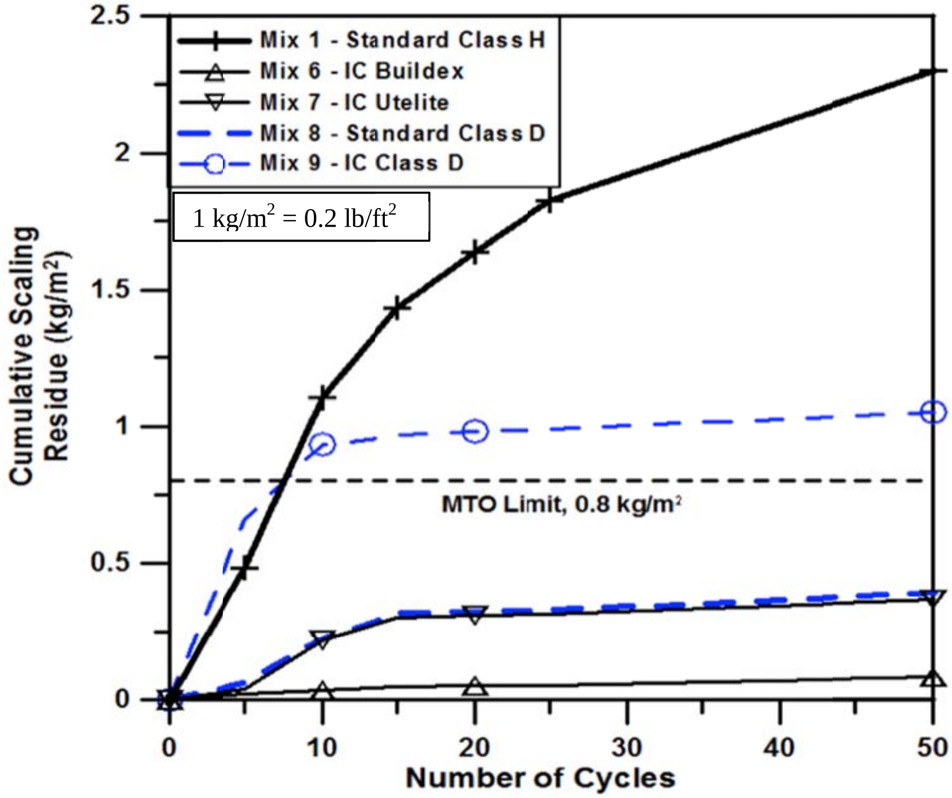


Figure 6.6: Plot of Mixtures 6-9 average cumulative scaling by ASTM C672 (2003) and MTO LS-412 scaling resistance to deicing chemicals. Mixture 1 is plotted again for reference.

Table 6.4: Summary of ASTM C672 (2003) and MTO LS-412 scaling resistance to deicing chemicals data for optimized mixture designs.

Scaling Resistance of Optimized Mixtures: Summary at 50 Cycles					
	Sample	Rating (1-5)	Average Rating	Cumu. Mass Loss (kg/m^2)	Avg. Cumu. Mass Loss (kg/m^2)
Mix 6 - IC Buildex	1-1	2-	2-	0.07	0.08
	1-2	2		0.09	
	1-3	2-		0.08	
Mix 7 - IC Utelite	3-1	3+	3+	0.15	0.19
	3-2	3+		0.29	
	3-3	3-		0.15	
Mix 8 - Standard Class D	4-1	3	2-	0.70	0.39
	4-2	2		0.30	
	4-3	2		0.17	
Mix 9 - IC Class D	5-1	3-	3-	0.99	1.05
	5-2	3-		1.11	
	5-3	3-		1.05	

1 kg/m^2 = 0.2 lb/ft^2

6.4 Summary and Conclusions

This chapter investigated the resistance to scaling and rapid freeze-thaw durability of both standard and internally cured Colorado DOT Class H and D mixtures. Results from this chapter can be summarized as follows:

- Rapid freeze-thaw was conducted as a close to “worst case scenario” situation, i.e., specimens were directly placed into the testing chamber from a sealed condition. This is done to clearly identify which mixtures perform poorly in freeze-thaw conditions, not to replicate field conditions.
- “Excessively” internally cured mixtures, i.e., mixtures that have more pre-wetted LWA than is required to replace water lost due to chemical shrinkage, have the potential to not perform well in freeze-thaw environments.
- Excess, unused, water from LWA present in a concrete system is not favorable in freeze-thaw conditions, as this excess water fills in pores, eliminating the aid that empty pore space provides in room for expansion of freezing water.
- Scaling is highly dependent on finishing. The main point to take from these results is that the Class H IC mixtures do not perform any worse than the standard Class H mixture. The Class D IC mixture does perform worse than the standard Class D mixture in scaling, but not any worse than the standard Class H mixture.
- Large replacements of LWA could results in alteration of thermal properties and could potentially aid in scaling. However, if used for IC purposes the internal integrity of the concrete will be lost, as previously discussed.

CHAPTER 7. EVALUATION OF SHRINKAGE PROPERTIES

7.1 Introduction

The objective of this study is to investigate the performance of internally cured, high performance concrete for potential use by the Colorado DOT. In particular, this study evaluates a series of internally cured high performance concrete mixtures, as noted in Table 4.1, for the Colorado DOT that meet the specifications of a Class H and Class D concrete. The use of internal curing in high performance concrete can increase the resistance to early-age cracking and enhance durability (Bentz and Weiss, 2011).

This chapter presents the results of the nine mixtures with respect to their shrinkage properties. Autogenous shrinkage, restrained shrinkage cracking, and free shrinkage in a 50% relative humidity (RH) drying condition were investigated. The test methods and casting procedures will be discussed first, followed by the results and discussions presented in a systematic order, in which the preliminary mixtures will be presented, followed by the optimized mixtures for each test being discussed.

7.2 Mixing, Placing, and Curing Procedures

Materials were batched and mixed in accordance to the procedure presented in Section 4.3 for restrained shrinkage (dual rings) and free shrinkage in a 50% RH drying condition (length change). Mixtures for early age autogenous shrinkage were cast separately using a Hobart paddle, 0.25 ft^3 capacity, mixing bowl.

In order to control aggregate pinching in the Hobart mixing bowl, a different mixing the one discussed for the pan mixer was used. The fines, cementitious material, admixtures, and mixing water were mixed first to create a fresh mortar. The time at which contact of water and cementitious material occurred was noted followed by the addition of the coarse aggregate. For internal curing mixtures, the LWA would soak in the required mixing water (including the water required to replace chemical shrinkage) for a 24 ± 1 hour period prior to mixing. Values of LWA absorption for a 24-hour period were used in the mixture designs for these tests. The curing methods used for each experiment will be discussed individually where applicable.

7.2.1 Chemical Shrinkage

The goal of internal curing is to replace water that is consumed by the hydration reaction (i.e., chemical shrinkage). Chemical shrinkage is defined as "the volume reduction associated with the reaction between cement and water in hydrating cement paste" (Bentz, 1995). While a typical chemical shrinkage for portland cement is on the order of 0.07 mL/g cement, the values for fly ash and slag can be 2 and 3 times greater, respectively (Bentz, 2007). As previously noted, this study used cement and fly ash from suppliers available in the Colorado area. If other cements/ cementitious materials are used, it is necessary that a chemical shrinkage test be performed on the cementitious materials before creating a mixture design.

For any binder of interest, the chemical shrinkage of a paste specimen is measured using the ASTM C1608 (2007) standard test method. The test was performed on a mixture with a 20% replacement of portland cement with fly ash, by mass (as is the case with the investigated concrete mixtures). The binder was mixed using a Twister Evolution 120V high shear (vacuum) mixer. The dry materials mixed for 15 seconds at 350 rpm, followed by the addition of water with mixing for 90 seconds at 350 rpm. The walls were and blades were then scraped to and the mixing continued for 60 seconds at 450 rpm. Three glass vials were filled with approximately 5mm of paste. Clean, de-aerated water was then filled to the top of the vial, with caution to not disturb the paste. A stopped and graduated capillary tube was inserted into the vial. The capillary tube was then filled with water filled to the top. Measurements were then taken visually every 30-60 minutes for the first 8 hours and at a 24-hour period. They were then monitored periodically over the following month. A control tube to monitor evaporation was also considered and corrections were made in the chemical shrinkage calculations.

7.2.2 Autogenous Shrinkage

Before discussing the testing methodologies, it may be beneficial to provide an understanding of autogenous shrinkage. This form of shrinkage is defined as the volume change occurring with no moisture being transferred to the surrounding environment. Autogenous shrinkage is a result of chemical shrinkage. It is an external volume reduction under isothermal, sealed conditions. An illustrative comparison of chemical shrinkage and autogenous shrinkage can be seen in Figure 7.1 to better understand these descriptions.

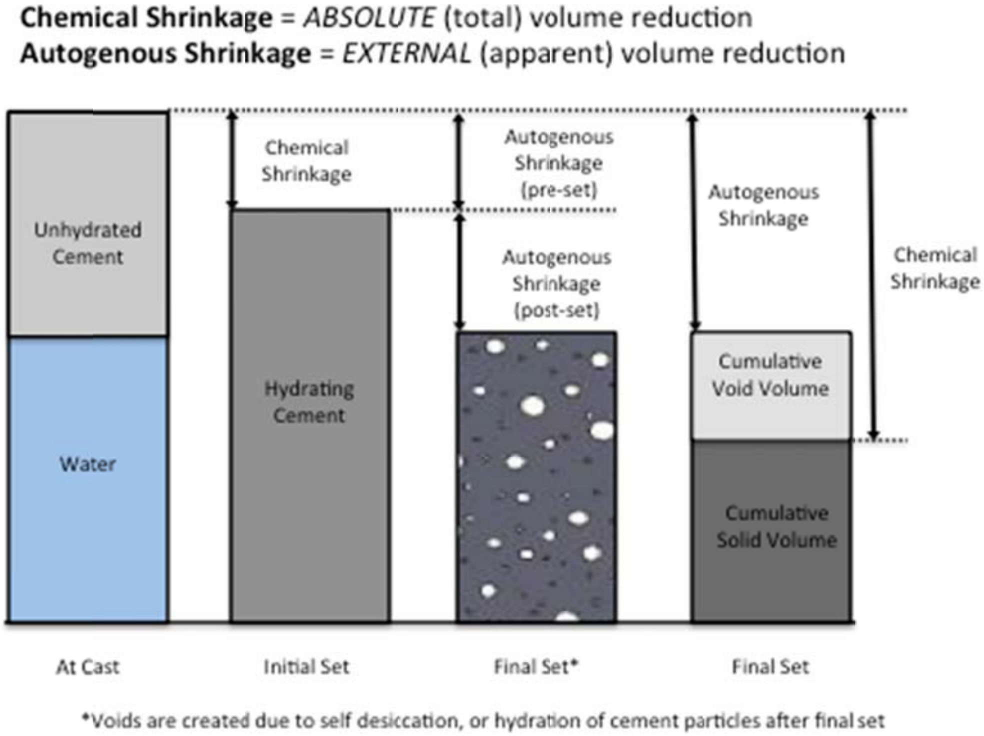


Figure 7.1: Illustration of the difference between chemical and autogenous shrinkage

Based on the protocol developed for cement paste (Jensen et al., 1995), a modified version of ASTM C1698 (2009), the standard test method for measuring autogenous strain of cement paste and mortar, was used to account for the role of coarse aggregates in the system. Concretes containing coarse aggregates are of interest for this study, as some mixtures rely on these larger aggregates for the source of internal curing. An image of the modified autogenous strain test can be seen in Figure 7.2. The figure shows a corrugated tube, in which concrete is placed via rodding and vibration in 3 lifts, paying close attention to be sure each rib of the tube is filled. A corrugated tube is used to allow for expansion in the longitudinal direction, while providing stiffness in the radial direction. Immediately after casting, the tube is placed in the testing apparatus. Concrete is place in the tube such that it is completely sealed and placed on a “friction free” base to allow for unrestricted expansion and contraction. The room in which the test is run is kept constant at 50 ± 1% RH and 23 ± 1°C. A linear variable differential transformer (LVDT) displacement transducer was placed at each end of the tubes to automatically measure changes in length over time.

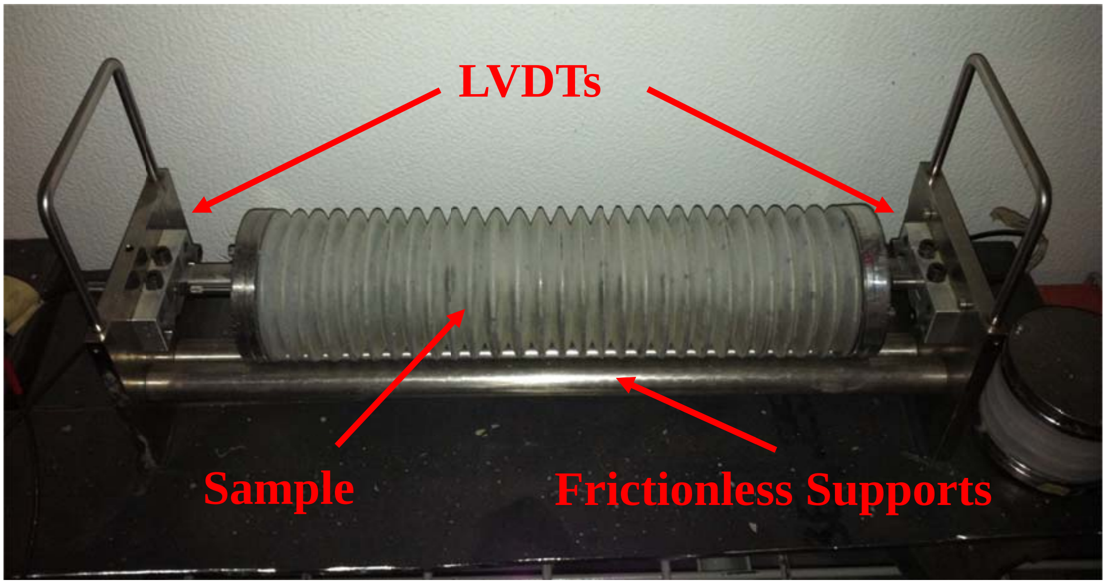


Figure 7.2: Modified version of ASTM 1698 (2009) to measure the autogenous shrinkage of a concrete specimen.

7.2.3 Restrained Shrinkage

The dual ring test was used to quantify the stress that is due to deformations of each of the desired mixtures. Similar to ASTM 1581 (2009a), single ring, the concrete dual ring test was built specifically to monitor both expansion and contraction in the mixtures. It consists of two instrumented concentric invar restraining rings that operate in an insulated and temperature controlled chamber (Radlinska et al., 2007; Schlitter et al., 2010;

Schlitter et al., 2011). For this test, a concrete specimen was cast between the inner and outer rings in two lifts, being vibrated after each lift, then trowel finished. The rings and concrete specimen sit upon a base plate, which is temperature controlled through a water bath. See Figure 7.3 for an image on the dual ring setup. After casting, the water bath is used to maintain a constant temperature. The rings, concrete specimen, and base plate are then placed inside an insulted chamber to maintain a constant temperature and humidity for a defined period of time. This eliminates any effects that could be attributed to thermal and drying stress buildup.

After 7 days of isothermal stress buildup the temperature of the plate drops at a rate of 2°C/hour to create large stresses in the sample. This rate is very important, as it has been shown to control temperature gradients in the concrete specimen (Schlitter et al., 2011). Based on geometry, the inner and outer rings have an approximate degree of restraint (DOR) of 70% and 40%, respectively. Strain measurements were automatically recorded and used to determine the stress buildup and age of cracking in the sample.

Figure 7.3: Dual ring test used to monitor stresses while creating restrained boundary conditions for the concrete

7.2.4 Drying Shrinkage

The drying shrinkage was measured in accordance with ASTM C157 (2008), the standard test method for length change of hardened hydraulic concrete. It should be noted that this test method measures the sum of drying and autogenous shrinkage, as the first measurement is taken after a time of 24 hours after casting. Sets of three 3 in wide by 3 in tall by 11 ¼ in long [75 mm by 75 mm by 285mm] samples were cast for each mixture to study the drying shrinkage. Gage studs were embedded into the ends of each sample. The specimens were cast in two lifts, being rodded 25 times and vibrated after each lift, and then trowel finished on the top surface. After a 24 ± 2 hour period the specimens were removed from the molds and an initial comparator reading was obtained. They were then bag sealed, and placed in a moist chamber at 23 ± 1°C [73.5 ± 1.5 °F] for a 28-day curing period. After the curing period, the specimens were removed from the sealed condition and a comparator reading was taken. The concrete specimens were then placed in a 50 ± 1 %RH and 23 ± 1°C chamber for drying.

7.3 Results and Discussions

7.3.1 Chemical Shrinkage

A plot of chemical shrinkage over time can be seen in Figure 7.4. As noted earlier in this report, to create mixture design and begin casting, the investigative team assumed a chemical shrinkage value of 0.064 mL/g. From the data presented in Figure 7.4 an ultimate chemical shrinkage value was estimated to be 0.075 mL/g, therefore the initial assumption is valid. The ultimate chemical shrinkage value represents the total chemical shrinkage at 100% degree of hydration. This was determined through linear extrapolation by plotting the chemical shrinkage against the inverse of a time and estimating the intercept (i.e., chemical shrinkage at an infinite time). A 100% degree of hydration, or ceasing of chemical shrinkage, is estimated to be around 185 days for this blend of cement and fly ash.

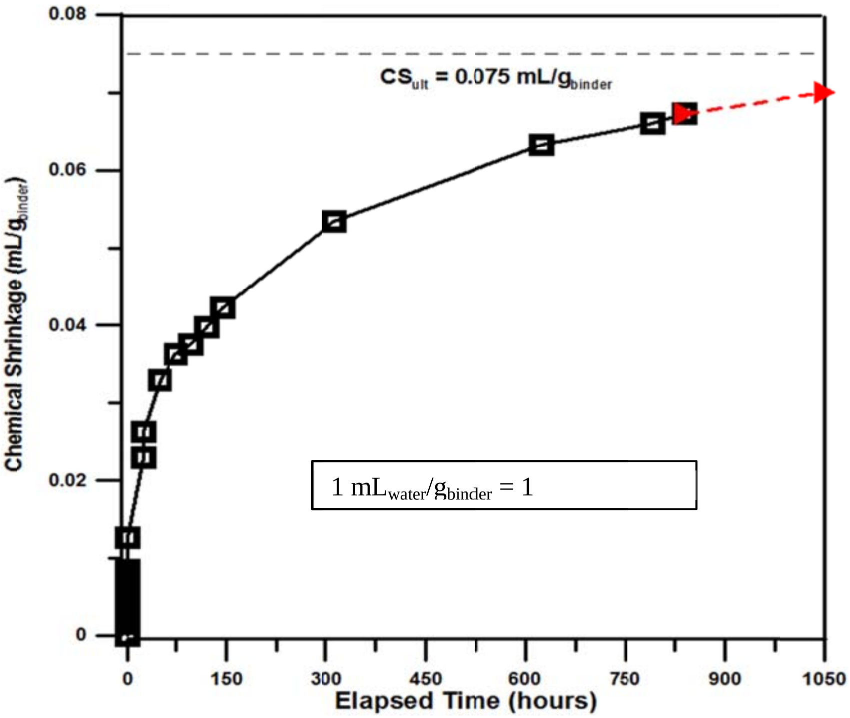


Figure 7.4: Plot of average chemical shrinkage, in mL per gram of cementitious binder.

7.3.2 Autogenous Shrinkage

7.3.2.1 Preliminary Mixtures

The results of the preliminary mixtures from autogenous shrinkage can be seen in the following figures. Figures 7.5 (a) – (e) present the strain due to sealed, isothermal volumetric changes in the concrete. The data presented monitors autogenous deformations and temperature for a period of 7 days. Negative values represent shrinkage of the material, while positive values represent expansion. The results presented are the deformations corrected to the time of set, which was assumed to be a constant value for all presented mixture. A time of 6 ½ hours was chosen based on a derivative analysis for the standard mixture (Sant et al., 2009).

Figure 7.5 (a) presents the results of the standard Class H mixture, in which autogenous *shrinkage* was measure up to approximately 30 microstrain. IC mixtures, as seen in Figures 7.5 (b), (c), (d), and (e) show swelling (or expansion) in the concrete, which is caused from the water present in the LWA. As the cementitious material hydrates, the water 'pushes' into the pores, causing expansion of the overall system. As time increases the water will redistribute in the matrix and swelling will subside. The swelling starts to reduce in 'Mix 2 – LWFA 1 x CS' as the age of the specimen approaches 7-days. If the autogenous strain were to be measure over much longer period of time, the concrete will relax and the measured strain would be nearly zero.

Figure 7.5 (c), where 2X the amount of chemical shrinkage is replaced with LWA fines, shows larger initial swelling than the standard replacement, Figure 7.5 (b). Figure 7.5 (d) displays a similar behavior to that of Figure 7.5 (b). It was earlier noted that proper distribution of aggregates for IC purposed couldn't be achieved with coarse LWA. While this still holds true, the expansion seen here is likely occurring simply due to water leaving the LWA pores, as it does in the other IC systems, pushing outwards and creating expansive forces.

Note the y-axis in Figure 5.7 (e), as Mixture 5 has so much excess water that it continues swelling over the 7-day period by trying to force water through the pore space. At some point later in time the swelling would eventually subside, however it would take a much longer time than the other mixtures presented here.

7.3.2.2 Optimized Mixtures

The results of the optimized mixtures from autogenous shrinkage can be seen in the following figures. Figures 7.6 (a) – (d) present the strain due to sealed, isothermal volumetric changes in the concrete. The data presented monitors autogenous deformations and temperature for a period of 7 days. Negative values represent shrinkage of the material, while positive values represent expansion. The results presented are the deformations corrected to the time of set, which was assumed to be a constant value for all presented mixture. A time of 6 ½ hours was chosen based on a derivative analysis for the standard mixture (Sant et al., 2009).

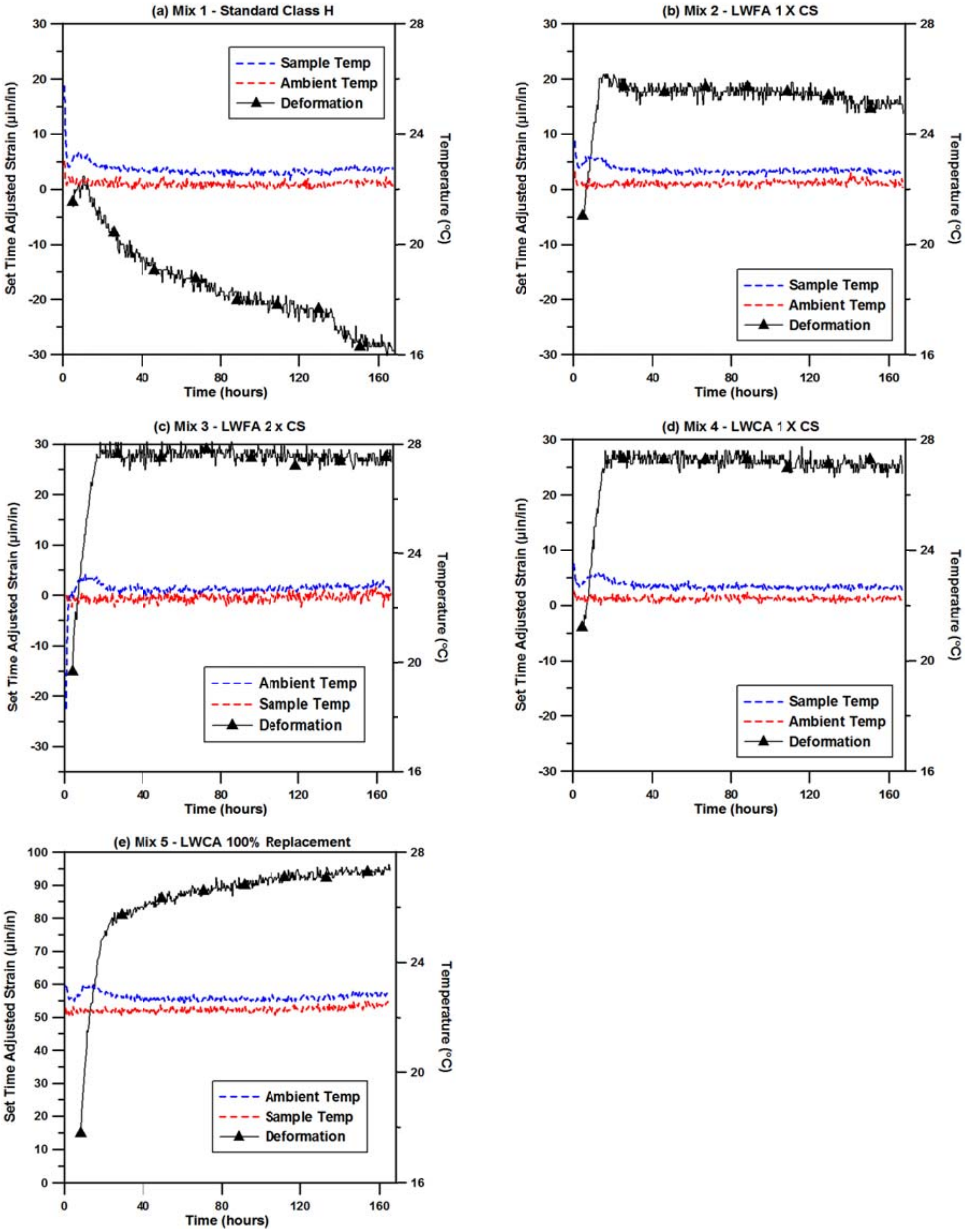


Figure 7.5: Results for the autogenous strain developed in the preliminary mixtures, mixtures 1 – 5, are shown in figures (a) – (e), respectively.

The ‘recommended dosage’ internally cured mixture from different suppliers, i.e., Figures 7.6 (a) and (b), display the same response as seen in the Figure 7.5 (b). These mixtures demonstrate initial swelling with eventual relation after water has been pulled from the LWA pores. Figures 7.6 (c) and (d) look relatively similar, in which there is initial expansion from the mixture followed by relaxation. Figure 7.6 (c), Mix 8 - Standard Class D, shows a little shrinkage towards the end of the testing life, where Figure 7.6 (d) relaxes to a value of zero. This similarity is likely due to the nature of the higher w/c.

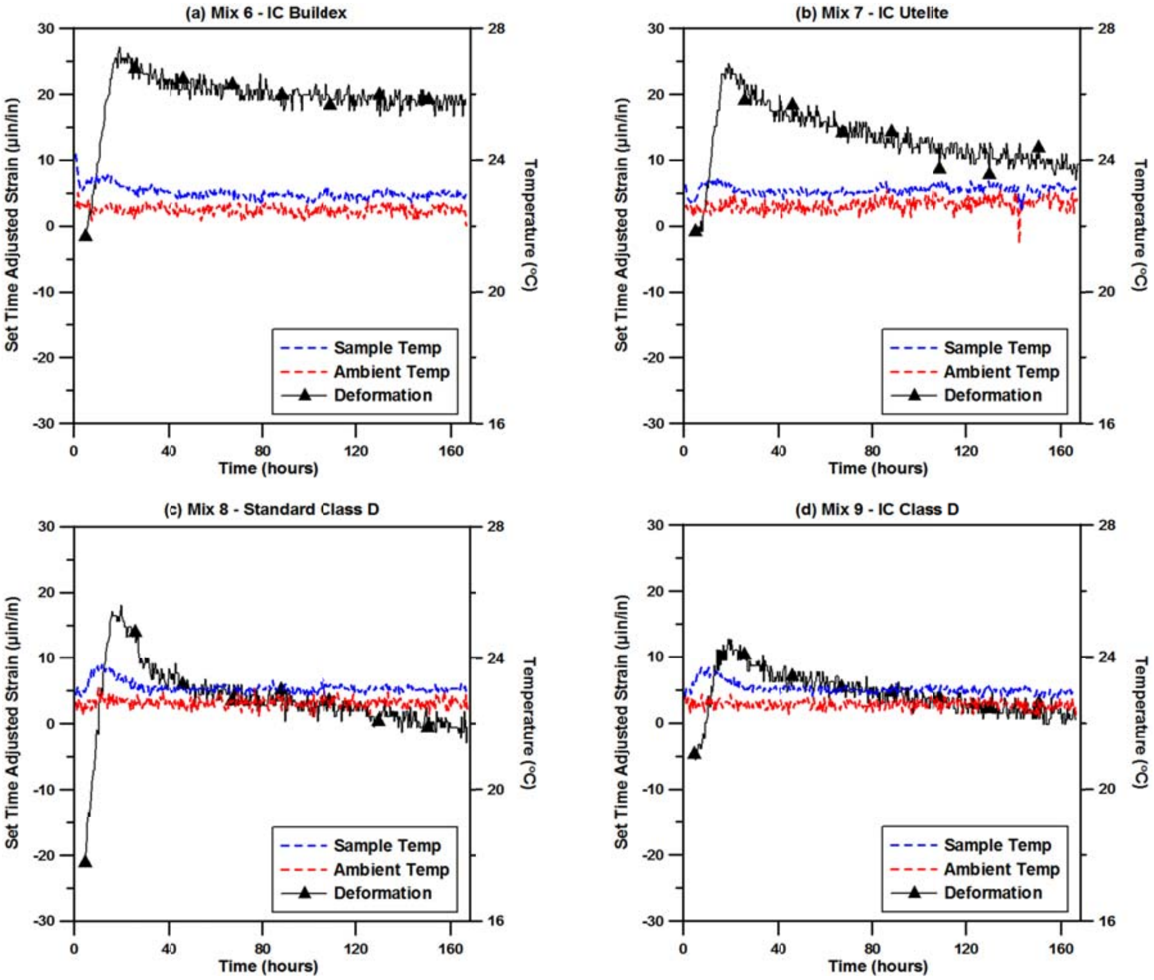


Figure 7.6: Results for the autogenous strain developed in the optimized mixtures, mixtures 6 – 9, are shown in Figures (a) – (d), respectively.

7.3.3 Restrained Shrinkage

It will be noticed that each of these mixtures has relatively low amounts of shrinkage occurring in the system. Past dual ring experience has shown a high stress buildup in plain mixtures and relatively low stress in IC mixtures (Schlitter et al., 2010). However, those mixtures consisted of mortar, having much higher paste contents. Introducing coarse aggregate into the cement matrix removes a large amount of paste and adds a higher degree of restraint to shrinkage in the system. Since it was decided in this study to fix the cementitious material content at an average value of the range provided in

Colorado DOT Specification Section 601 (2001a; 2011b), a relatively high total aggregate content of 74% was used (as noted in Section 4.2 of this report). A general rule of thumb for controlling shrinkage in concretes is to replace the part of the system that shrinks (i.e., paste) with more of what doesn't shrink (i.e., coarse aggregate).

These mixtures also have a relatively high w/c, in which large capillary pores form. Since stress buildup is related to the size of pores being emptied, a much larger difference would be noticed between the plain and IC mixtures if a lower w/c were used. Therefore, the reason for such low shrinkage in the standard mixture is due a high aggregate content (which replaces paste content) and that the w/c is high, which accommodates shrinkage in the system.

7.3.3.1 Preliminary Mixtures

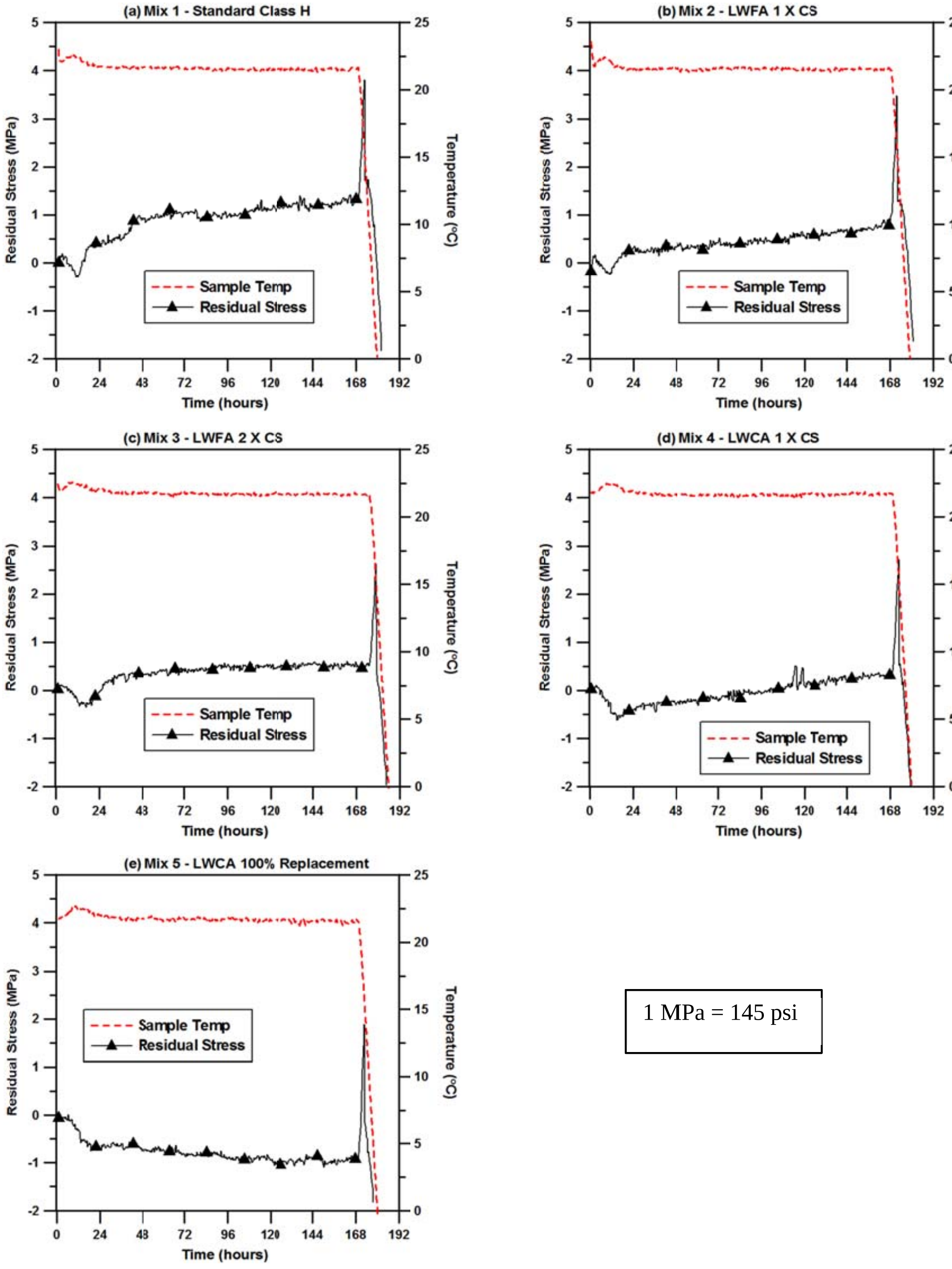
The results of the preliminary mixtures from restrained shrinkage can be seen in the following figures. Figures 7.7 (a) – (e) present the tensile stress buildup due to restrained conditions in an isothermal environment. The data presented monitors the residual tensile stress development for a period of 7 days, at which point the temperature is dropped at a rate of 2°C/hour until a significant crack develops, or a temperature of -9°C is reached (none of the mixtures evaluated reached a temperature of -9°C before significant crack developed). Significant crack development refers to the peak in the data in which stress rapidly changes to a highly negative value, attributed to crack propagation. The increasing slope prior to cracking is often referred to as the reserve capacity of the sample. The results presented are the tensile stress developments that have been corrected to the time of set, assumed to be a constant value for all presented mixture. A time of 6 ½ hours was chosen based on a derivative analysis from autogenous shrinkage (Section 7.3.2).

Figure 7.7 (a) presents the results of the standard Class H mixture, in which stress development occurred for the first 7 days, at which time the temperature dropped. The “flatter” curves for the IC mixtures, as seen in Figures 7.7 (b), (c), (d), and (e), represent less stress buildup/ shrinkage in the sample. A negative stress, or expansive force, is noticed for approximately the first 4 days in Figure 7.6 (d) and up to the point of temperature drop in Figure 7.7 (e). This is likely due to the phenomena of swelling, in which water is pushing its way through the system, as was described in Section 7.3.2.

The take-away from these results is that a lower stress is developed for IC mixtures than for mixtures not utilizing IC methods. This is more apparent in lower w/c mixtures where smaller pore sizes are being emptied through chemical shrinkage and self-desiccation, or in mixtures containing high paste contents.

7.3.3.2 Optimized Mixtures

The results of the optimized mixtures from restrained shrinkage can be seen in the following figures. Figures 7.8 (a) – (d) present the tensile stress buildup due to restrained conditions in an isothermal environment. The data presented monitors the residual tensile stress development for a period of 7 days, at which point the temperature is dropped at a rate of 2°C/hour until a significant crack develops, or a temperature of -9°C is reached (none of the mixtures evaluated reached a temperature of -9°C before significant crack developed). Significant crack development refers to the peak in the data in which stress rapidly changes to a highly negative value, attributed to crack propagation. The increasing slope prior to cracking is often referred to as the reserve capacity of the sample. The results presented are the tensile stress developments that have been corrected to the time of set, assumed to be a constant value for all presented mixture. A time of 6 ½ hours was chosen based on a derivative analysis from autogenous shrinkage (Section 7.3.2). Figures 7.8 (a) and 7.8 (b) represent the residual tensile stress buildup for IC mixtures with additional LWA suppliers, Buildex and Utelite, respectively. Both mixtures show similar results to that of Figure 5.6 (b), where the same mixture design is used, however other LWA were substituted. Figures 7.8 (c) and (d) present the dual ring



1 MPa = 145 psi

Figure 7.7: Results for the residual tensile stress developed in the preliminary mixtures, mixtures 1 – 5, are shown in figures (a) – (e), respectively.

results for the Class D mixture. It can be seen that the standard Class D mixture does not have a significant stress buildup, as the mixture has a 0.45 w/c. This agrees with the notion that high residual stresses are not developed in mixtures where large capillary pores are formed, i.e., high w/c mixtures. Consequently, no notable differences can be observed from the standard to IC Class D mixture, as it relates to restrained shrinkage. Furthermore, the Class D mixtures crack (or are relieved of positive stress formation) at a lower residual tensile stress, approximately 1-2 MPa lower.

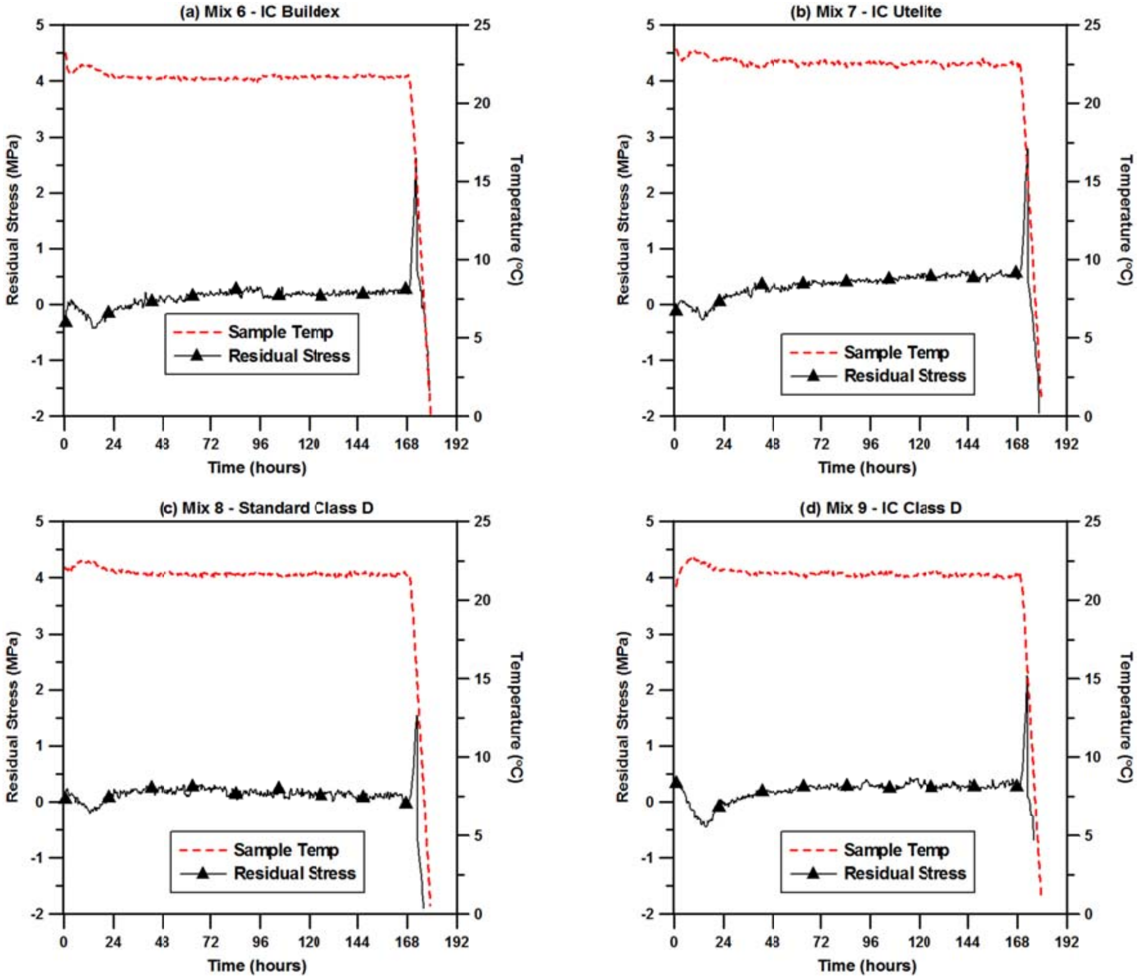


Figure 7.8: Results for the residual tensile stress developed in the optimized mixtures, mixtures 6 – 9, are shown in figures (a) – (d), respectively.

7.3.4 Drying Shrinkage

The results from ASTM C157 (2008), monitoring of length change in a drying condition, are presented in this section. Once the initial measurements were recorded (24 hours after water-cement contact), the samples were bag sealed and placed in a moist curing chamber until an age of 28 days. After the curing period, and prior to exposure to drying, length measurements were taken. This is what is referred to as the ‘zero time’ length change in the following plots. The zero time length measurement captures the shrinkage that has taken place without exposure to drying. With that being said, one should be recognize that this test does not capture early age shrinkage (i.e., the first 24 hours). This has been shown in the previous sections to be an important part in quantifying total shrinkage of concrete.

The results shown are an average of three samples, where length change, ΔL_x, is calculated by Equation 7.1, in which CRD is the difference between the comparator reading and reference bar at any age and G is the gage length (in this case G = 10in).

$$\Delta L_x = \frac{CRD - CRD_{initial}}{G} \tag{7.1}$$

7.3.4.1 Preliminary Mixtures

The drying shrinkage results for the preliminary mixture can be seen in Figure 7.9. It is clear that all IC mixtures performed better that the standard Class H mixture. The IC mixtures have less shrinkage than the standard mixture after the 28 day period as well as throughout the exposure to drying. This is due to the fact that additional moisture is present in the matrix to keep the internal RH level higher for a longer period of time. In turn, this will help to minimize stress buildup when exposed to low RH environments. While most mixtures show a shrinkage response throughout curing, Mixture 5 shows expansion throughout the curing process. This is consistent with the autogenous shrinkage and restrained shrinkage test results.

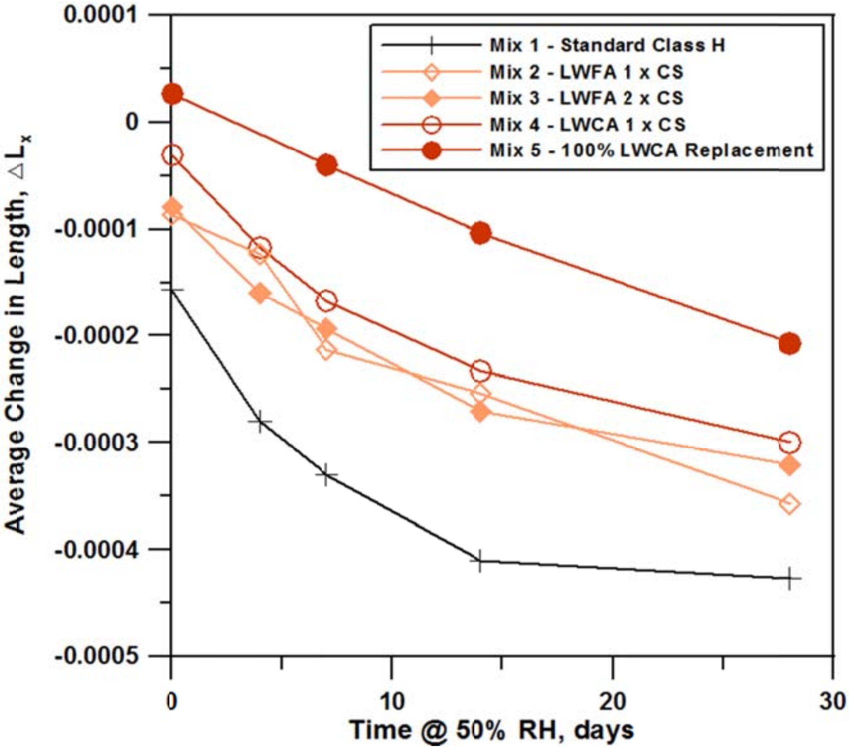


Figure 7.9: Preliminary mixture drying shrinkage results at 50% RH after 28 day sealed curing period, normalized to gauge length.

7.3.4.2 Optimized Mixtures

The drying shrinkage results for the optimized mixtures can be seen in Figure 7.10. As is the case with the preliminary mixture, all IC mixtures show benefits in drying shrinkage when compared to the respective standard Mixture. Mixtures 6 and 7, where alternative LWA suppliers were used, both show a decrease in shrinkage from standard Class H mixture. Additionally, the Class D mixture is also beneficial when IC practices are utilized.

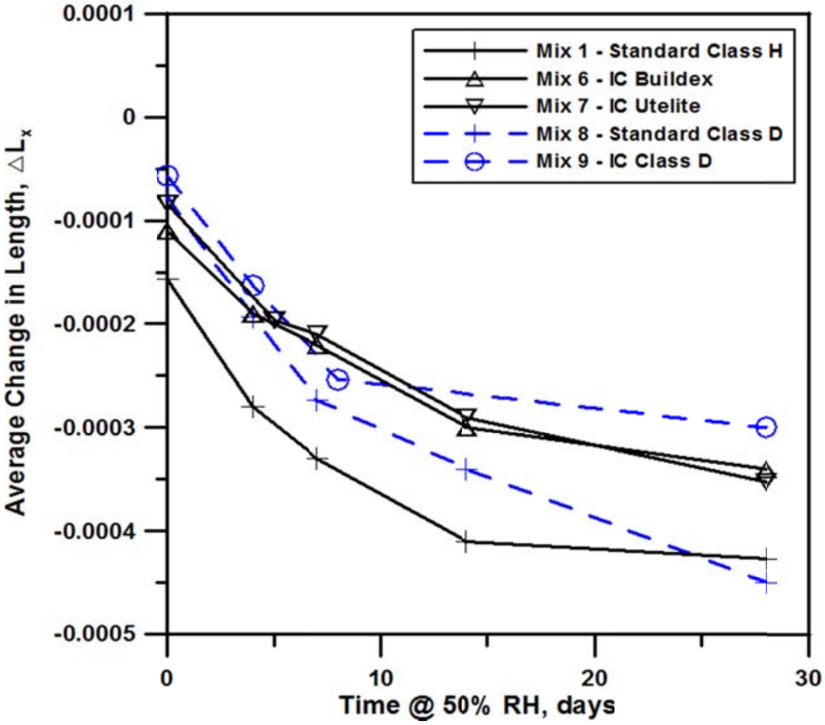


Figure 7.10: Optimized mixture drying shrinkage results at 50% RH after 28 day sealed curing period, normalized to gauge length.

7.4 Summary and Conclusions

This chapter investigated the shrinkage properties of both standard and internally cured Colorado DOT Class H and D mixtures. The shrinkage properties presented consist of the chemical, autogenous, restrained, and drying shrinkage for each of the nine mixtures. Results from this chapter can be summarized as follows:

- The chemical shrinkage was found to 0.07 g/mL of cementitious material for the mixture composition used in this study. Should any different cementitious material be used, another chemical shrinkage test should be performed.
- Internally cured mixtures prevent autogenous shrinkage and cause expansion (or swelling) in a sealed system. This expansion will eventually relax out over time and hydration of the cement subsides.
- Shrinkage of the 0.42 mixture was on the order of 30 micro-strain for the standard Class H mixture and the swelling 20 micro strain for the “recommended IC” (i.e., LWA used to replace the water lost to chemical shrinkage) mixtures.
- Restrained shrinkage showed that IC concrete reduced the residual stress buildup in the material, however this was not as apparent in these “higher” w/c mixtures as it would be when comparing a lower w/c with the IC counterpart. For example little difference was noted for the Class D mixture, in which a 0.45 w/c was used.
- Internally cured mixtures show improved drying shrinkage performance, since water is present in the matrix to continue hydration as the surface dries. However, one should realize the shortcomings of performing only the drying test, as the test does not account early age shrinkage.

CHAPTER 8. EVALUATION OF FLUID TRANSPORT PROPERTIES

8.1 Introduction

The objective of this study is to investigate the performance of internally cured, high performance concrete for potential use by the Colorado DOT. In particular, this study evaluates a series of internally cured high performance concrete mixtures, as noted in Table 4.1, for the Colorado DOT that meet the specifications of a Class H and Class D concrete. The use of internal curing in high performance concrete can increase the resistance to early-age cracking and enhance durability (Bentz and Weiss, 2011).

This chapter presents the fluid transport properties of the nine mixtures. The transport properties presented consist of porosity determination, water absorption, and ionic species transport for each mixture. The test methods and casting procedures will be discussed first, followed by the results and discussions presented in a systematic order, in which the preliminary mixtures will be presented, followed by the optimized mixtures for each test being discussed.

8.2 Mixing, Placing, and Curing Procedures

Materials were batched and mixed in accordance with the procedure presented in Section 4.3. For internal curing mixtures, the LWA would soak in the required mixing water (including the water required to replace chemical shrinkage) for a 72 ± 4 hour period prior to mixing. For transport property testing, water absorption and ionic transport, samples for testing were allotted at least a 91-day curing period in a sealed environment.

8.2.1 Ionic Transport

The diffusion coefficients, tortuosity, and permeability for ionic species were measured using STADIUM Lab software and a migration cell (SIMCO Technologies Inc., 2011). The test method is a modified version of ASTM C1202 (2012d), where electrical current passed that passes through a 4 in diameter by 2 in thick [100 mm by 50 mm] specimen was monitored over a 14-day period. The samples used for this test were cut from a set of 4 in diameter by 8 in long concrete cylinders that were sealed and placed in a chamber at moist and 23 ± 2 °C for a minimum of 91 days.

After the samples were cut in accordance with the STADIUM user manual (SIMCO Technologies Inc., 2011), the sides of the samples were sealed with an epoxy. They were then vacuum saturated with a 0.3 M NaOH solution in replacement of water. A vacuum condition was held at a pressure of 20 mm Hg at 60 ± 1 °C for 3 hours. Solution was then added to the samples, while remaining in a vacuum state to de-aerate the NaOH solution for an additional 1 hour. The vacuum was then turned off and the samples remained in the NaOH solution for a minimum time of 16 hours. Once saturated, the samples were mounted between a cell filled with 0.3 M NaOH solution (downstream) and a cell filled with 0.5 M NaCL + 0.3 M NaOH solution (upstream). A constant DC potential of 20V was maintained across the specimen for 14 days while the voltage, current, and temperature were measured and recorded. Refer to the STADIUM Lab user guide (SIMCO Technologies Inc., 2011) for an illustration of the SIMCO migration cells used for this portion of the study.

In conjunction with the migration cell testing, the volume of permeable voids of the samples was determined in accordance with ASTM C642 (2006), with the exception that the boiling water method of saturating the samples was replaced with vacuum saturation. Vacuum saturation was performed in the same manner as previously discussed in this section, with the exception of water being used in place of the NaOH solution.

Also in conjunction with the migration cell testing was the drying test, as prescribed by the STADIUM user manual (SIMCO Technologies Inc., 2011), for moisture transport properties. For this test sets of three 10 ± 1mm and three 50 ± 2 mm thick specimens, also with a 91 days curing time, were cut and epoxies along the sides. Per STADIUM user manual (SIMCO Technologies Inc., 2011), these samples were placed in limewater at least two weeks, until a constant mass had been obtained. They were removed from the limewater, which point the initial and buoyant masses were obtained. The samples were then placed in a 50 ± 1 %RH and 23 ± 1°C chamber for drying. The masses were monitored and recorded daily for the first week, every other day for the second week, and twice per week until a total of 30 days was reached.

The results from the migration cell, volume of permeable voids, and drying test were used in the STADIUM Lab software to evaluate the ion diffusion coefficients, tortuosity, and permeability of the samples. The values and reported and discussed in the results section.

8.2.2 Water Absorption

Water absorption was determined in accordance with a modified version of ASTM C1585 (2011d). Sets of 4 in diameter by 8 in tall [100 mm by 200mm], cylinders were cast to study the absorption rate of each mixture. The cylinders were cast in two lifts, being vibrated and rodded 25 times after each lift. After one day of curing in their molds, the cylinders were demolded, bag sealed, and stored in a moist chamber at a temperature of 23 ± 1 °C until testing, which occurred after 91 days. Upon completion of the curing period 4 in diameter by 2 in thick [100 mm by 50 mm] samples were cut from the middle 6 in section of these samples using a concrete wet saw. Once cut, the sides of the samples were sealed with epoxy. Samples for absorption testing were taken from different cylinders to eliminate bias.

Castro et al. (2011) have shown that the conditioning method prescribed by ASTM C1585 (2011d) can show large inconsistencies in the standardized absorption test. Therefore, a way to maintain consistency from mixture to mixture was necessary. To do this, the porosity of each mixture (determined in the previous section per ASTM C642) was used to determine a desired mass at which approximately 50% of the capillary voids would be filled with water.

The samples were then vacuum saturated by placing the samples in a vacuum condition at a pressure of 20 mm Hg at 60 ± 1 °C for 3 hours. Water was then added to the samples, while remaining in a vacuum state to de-aerate the water, for an addition 1 hour. The vacuum was then turned off and the samples remained in the water for a minimum time of 16 hours. A saturated surface dry mass for each sample was then obtained and a desired mass at was obtained. The samples were then placed in a vacuum oven with a pressure of 685 mm Hg at 60 ± 1 °C (the temperature is the maximum permissible temperature to avoid damaging of the microstructure), being monitored daily until the desired mass was reached. Once each sample obtained the desired mass for an estimated 50% filled capillary porosity, the samples were double-bag sealed for the same amount of time they were in the vacuum oven to allow for moisture redistribution.

Prior to testing, the tops of the samples were sealed with plastic and the initial mass was recorded. The samples were then placed on supports inside containers, which were filled with water such that the water level was approximately 1/8 in (3 mm) above the bottom of the sample. The mass of each sample was then taken at the prescribed intervals set forth in ASTM C1585 (2011d), with the test ending after 8 days of absorption.

Upon completion of the absorption testing, the degree of saturation of each of these samples was determined by first oven drying the samples until a mass equilibrium of ± 0.01% was reached. The samples were then vacuum saturated with water as previously described. Using the initial conditioned mass, the oven dry mass, and the saturated mass, the degree of saturation was calculated for each sample.

8.3 Results and Discussion

8.3.1 Ionic Transport

The following section presents results obtained through migration cell testing, including the volume of permeable voids (per ASTM C642 (2006) using vacuum saturation), the chloride diffusion coefficient, tortuosity, and permeability. The latter values are calculated using STADIUM Lab from the results of the migration cell and drying testing. The presented results are based on a simulation done by analysis of testing results along with the mixture design, cementitious material composition, volume of permeable voids, and sample geometry. It should be noted that the simulation is designed for standard mixture, i.e. not for mixture using LWAs. Therefore, using a weighted average for the specific gravity and combining the lightweight and normal-weight mixture design values for density, a manipulation to the inputs for IC mixtures was made.

8.3.1.1 Preliminary Mixtures

The results from the preliminary mixtures ionic transport testing can be seen in Table 8.1. Comparing the results shows a slight increase in porosity (about 10%) for the LWFA mixtures, which can be attributed to the addition of porous particles. This is demonstrated even more for the mixtures that introduce LWCA, in which the increase is up to about 80%. All preliminary IC mixtures show a decreased diffusion and tortuosity (which are directly proportional, as calculated by the software) by about 40% and 50%, respectively. This is due to an increased in hydration of the cementitious material, resulting in discontinuity of the pore structure. The permeability of mixtures 2 and 4 decreases while an increased permeability is seen for the others mixtures. While the permeability change for mixture 4 is negligible (compared to other changes) a decrease of about 25% is seen in mixture 2. The increase in permeability for mixture 3 and the drastic increase for mixture 5 can attributed to the large amounts of big pores that are present in the matrix.

Table 8.1: Preliminary mixture results for volume of porosity, chloride diffusion coefficients, tortuosity, and permeability determined through ASTM C624 (2006) and STADIUM Lab testing.

ID: Description	**Porosity (%)**	**D Cl^- (e^{-11} m^2/s)**	**Tortuosity**	**Permeability (e^{-22} m^2)**
Mix 1: Standard Class H	14.7	1.98	0.0097	2.65
Mix 2: LWFA 1 x CS	16.4	1.15	0.0057	1.94
Mix 3: LWFA 2 x CS	16.5	0.99	0.0049	3.47
Mix 4: CLWA 1 x CS	18.5	1.16	0.0057	2.35
Mix 5: 100% CLWA Replacement	26.7	0.92	0.0045	21.47

1 m^2 = 10.7 ft^2

8.3.1.2 Optimized Mixtures

The results from the optimized mixtures ionic transport testing can be seen in Table 8.2. Comparing the results shows a slight increase in permeable voids (about 10%) for the LWFA mixtures where two other suppliers were used (i.e., mixtures 6 and 7), which can be attributed to the addition of porous particles. The change in porosity from the standard Class D mixture to the Class D IC mixture is negligible. Mixtures 6 and 7 show about a 60% and 30% decrease in the diffusion coefficients and tortuosity from the standard Class H mixture, respectively. The diffusion and tortuosity for the IC Class D mixture decreases by about 65%. The permeability for mixtures 6 and 7 decrease from the standard Class H, however the IC Class D mixture increases in permeability.

Table 8.2: Optimized mixture results for volume of porosity, chloride diffusion coefficients, tortuosity, and permeability determined through ASTM C624 (2006) and STADIUM Lab testing.

ID: Description	**Porosity (%)**	**D Cl^- (e^{-11} m^2/s)**	**Tortuosity**	**Permeability (e^{-22} m^2)**
Mix 6: IC Buildex	16.2	0.83	0.0041	2.19
Mix 7: IC Utelite	16.9	1.33	0.0065	2.52
Mix 8: Standard Class D	17.2	2.76	0.0258	3.46
Mix 9: IC Class D	17.4	0.99	0.0049	4.06

1 m^2 = 10.7 ft^2

8.3.2 Water Absorption

The results of the ASTM C1585 (2011d) water absorption test and the associated change in degree of saturation (DOS) for each mixture can be seen in Figure 8.2 through Figure 8.10. Plot (a) shows the calculated absorption values (per ASTM C1585) with respect to the square root of time, in seconds. It should be noted that the calculation set forth by ASTM C1585 does not determine the maximum depth at which water has penetrated in the sample. The calculation is a mass based representation of the depth water would reach if the concrete volume was space was filled entirely with water, i.e., volume of voids is not a consideration in the calculation. Plot (b) shows the change in DOS with respect to time, in days. The DOS is calculated here as the ratio of the current amount of absolute absorbed water to the total possible amount of absorbed water. The initial and secondary sorption values, final water penetration depth, and initial and final DOS for each mixture are listed in Table 8.3 and Table 8.4. Note that the values listed in these tables are averages of the two samples tested. The advantage of normalizing the results by DOS is the ability to determine whether the specimens reach the suggested critical DOS of about 86%, beyond which freeze-thaw damage can initiate (Fagerlund, 1977; Li et al., 2011).

8.3.2.1 Preliminary Mixtures

Comparing the preliminary mixtures yields very similar results for absorption rates of internally cured mixtures to the standard mixtures. A slightly higher rate of initial absorption is likely due to the interface action from empty lightweight aggregate particles. The slightly higher secondary rate of absorption is also likely attributed to the lightweight aggregate particles, as the dry desorbed aggregate is taking in more water than the standard mixture. However, no significant differences are present in when comparing the standard and IC mixtures, with the exception of the mixtures that use coarse LWA. When the water absorption results are normalized to the change in DOS it can be seen that none of the mixtures reach the critical DOS, with the maximum DOS of any of these mixture being about 60% after 8 days of absorption testing.

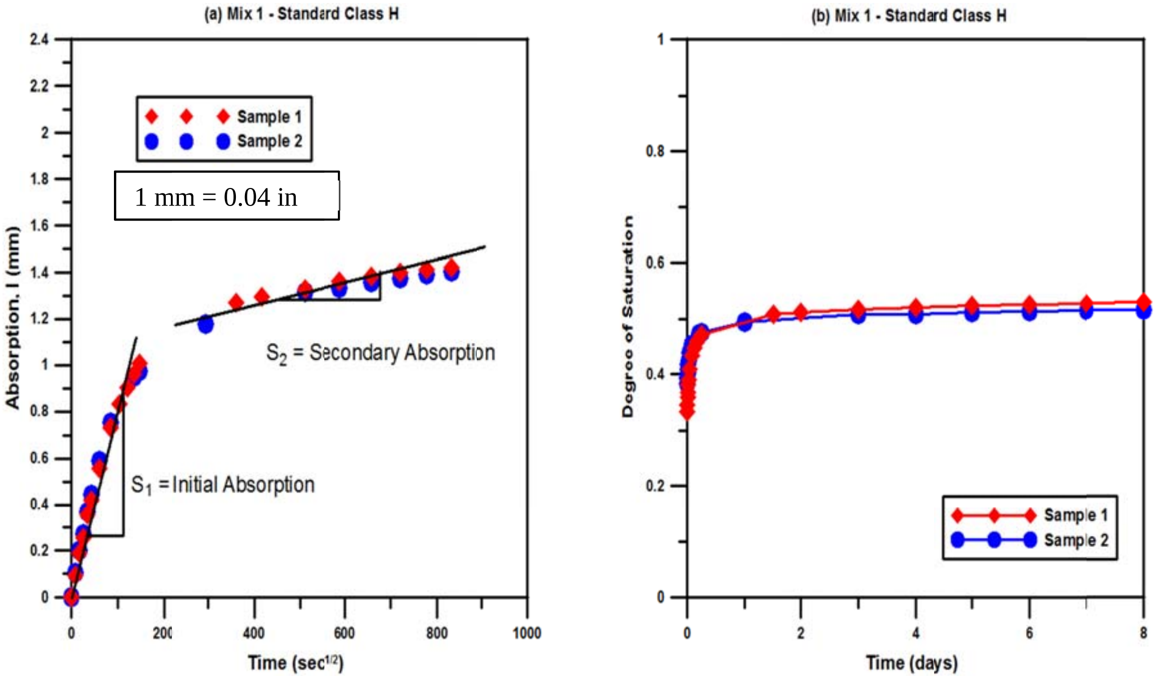


Figure 8.1: (a) Water absorption and (b) change in DOS for Mixture 1 – Standard Class H

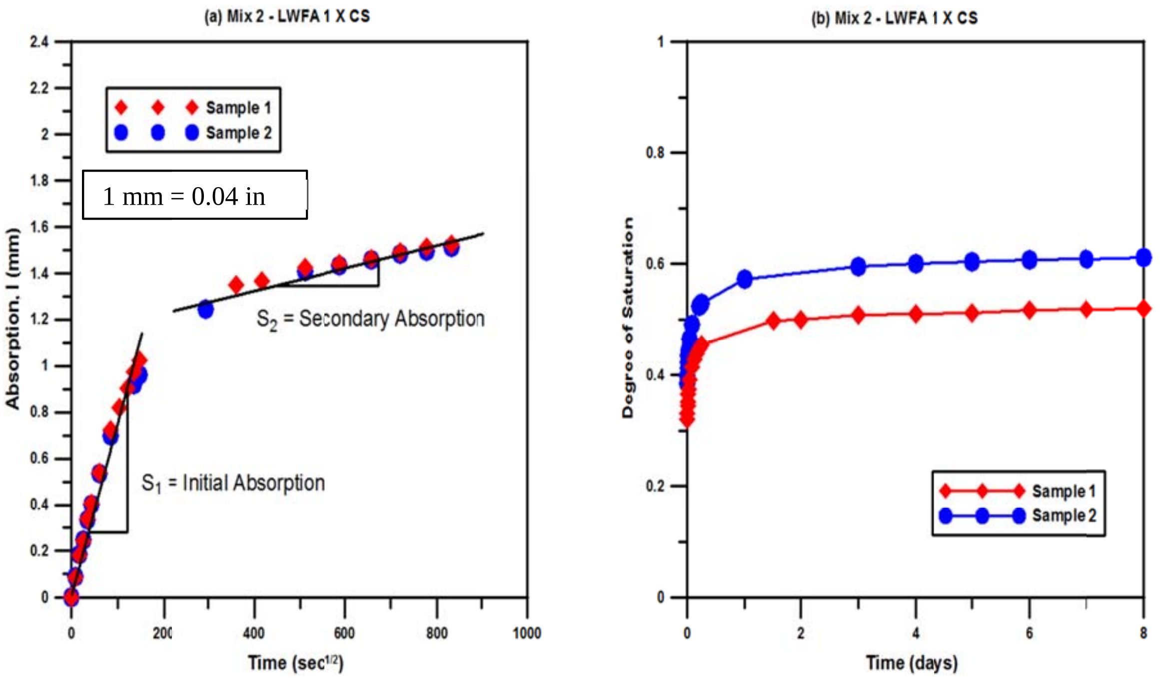


Figure 8.2: (a) Water absorption and (b) change in DOS for Mixture 2 – LWFA 1 X CS

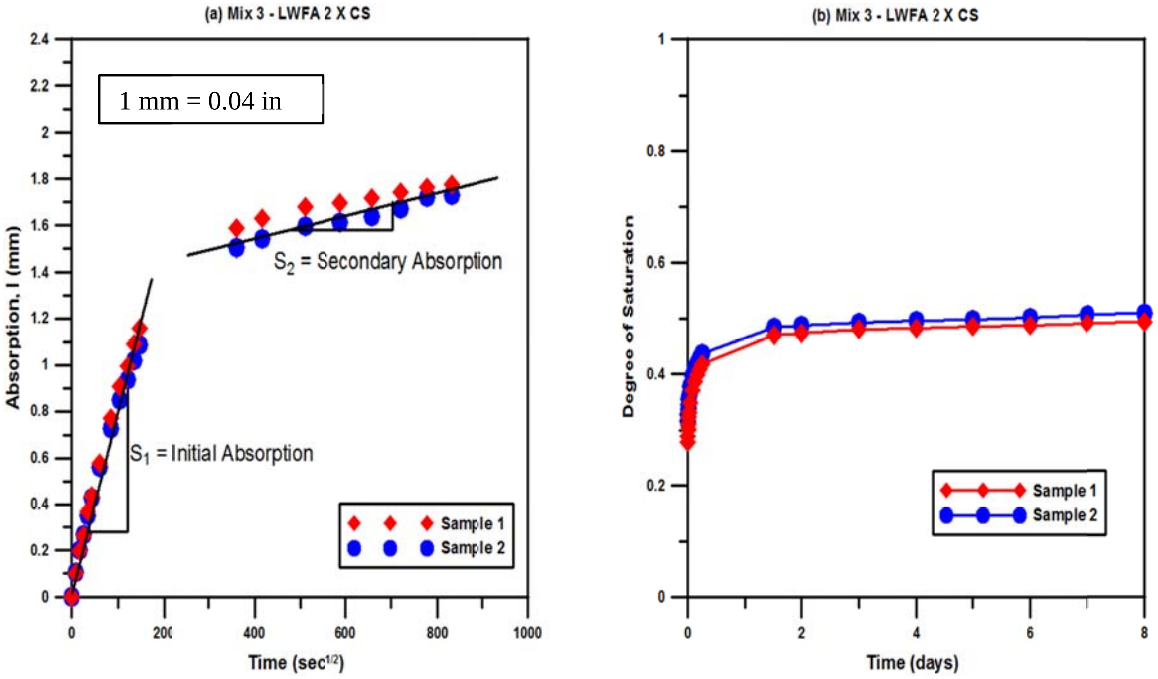


Figure 8.3: (a) Water absorption and (b) change in DOS for Mixture 3 – LWFA 2 X CS

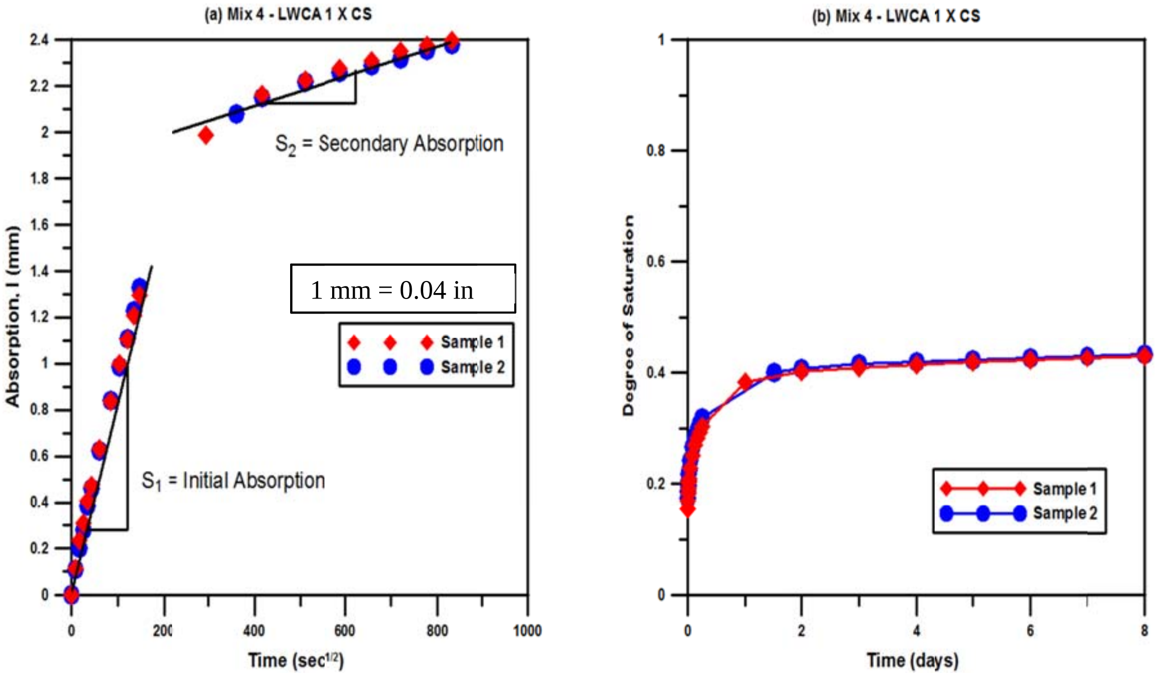


Figure 8.4: (a) Water absorption and (b) change in DOS for Mixture 4 – LWCA 1 X CS

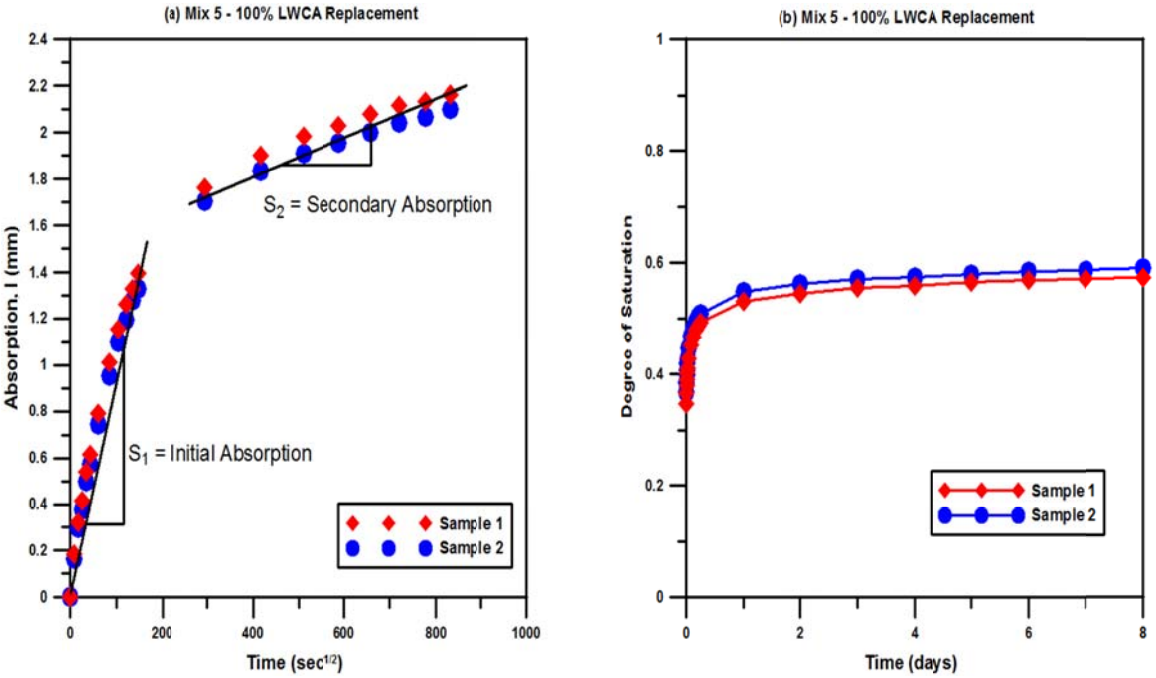


Figure 8.5: (a) Water absorption and (b) change in DOS for Mixture 5 – 100% LWCA Replacement

Table 8.3: Tabulated values for the initial and secondary absorption rates, 8-day depth of water penetration (I, mm), and the initial and 8-day DOSs of the preliminary mixtures

Mixture ID	**S_1 (mm/sec$^{1/2}$)**	**S_2 (mm/sec$^{1/2}$)**	**$I_{8\text{-day}}$ (mm)**	**Degree of Saturation (%)**	
				Initial	**8-day**
Mix 1: Standard Class H	6.66E-03	3.49E-04	1.41	36%	53%
Mix 2: LWFA 1 x CS	6.68E-03	4.02E-04	1.52	36%	57%
Mix 3: LWFA 2 x CS	7.49E-03	4.20E-04	1.75	30%	50%
Mix 4: CLWA 1 x CS	8.72E-03	6.57E-04	2.39	17%	43%
Mix 5: 100% CLWA Replacement	8.91E-03	7.19E-04	2.13	36%	59%

8.3.2.2 Optimized Mixtures

Comparing the optimized mixtures yields very similar results for absorption rates of internally cured mixtures to the standard mixtures. A slightly higher rate of initial absorption is likely due to the interface action from empty lightweight aggregate particles. The slightly higher secondary rate of absorption is also likely attributed to the lightweight aggregate particles, as the dry desorbed aggregate is taking in more water than the standard mixture. The higher sorption rate for mixture 7 is likely due to the larger absorption capacity of Utelite aggregate (as shown in Section 3.3.2). Mixture 9 has a large sorption rate than mixture 8, which may be due to the lower initial degree of saturation. When the water absorption results are normalized to the change in DOS it can be seen that none of the mixtures each the critical DOS, with the maximum DOS of any of these mixture being 77% after 8 days of absorption testing.

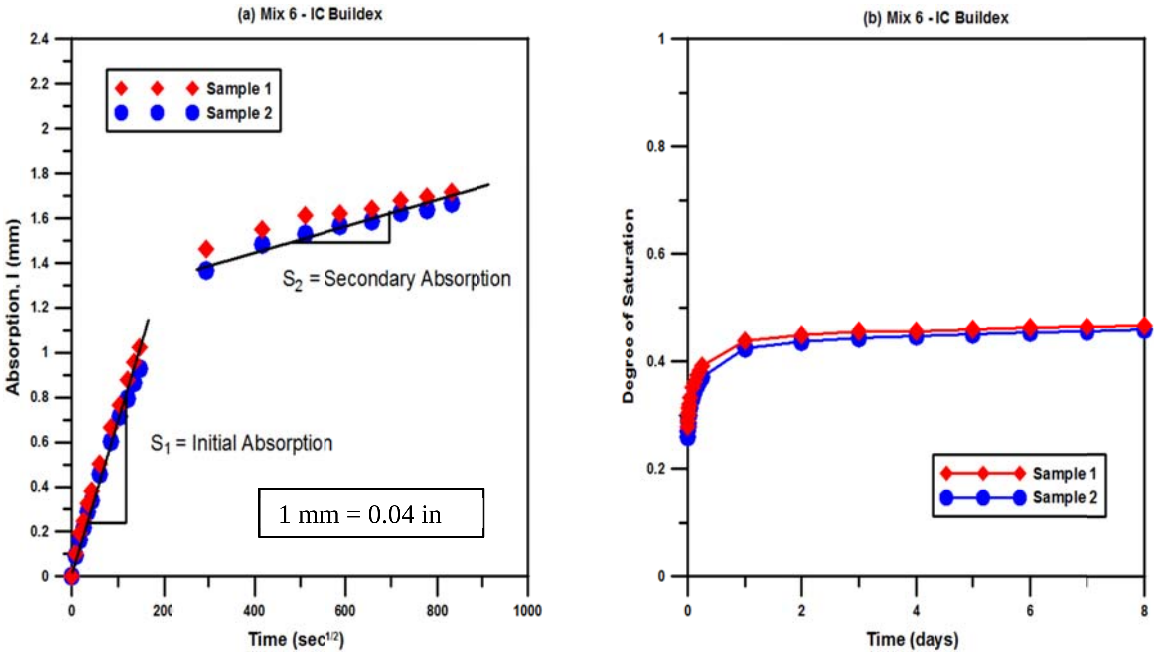


Figure 8.6: (a) Water absorption and (b) change in DOS for Mixture 6 – IC Buildex

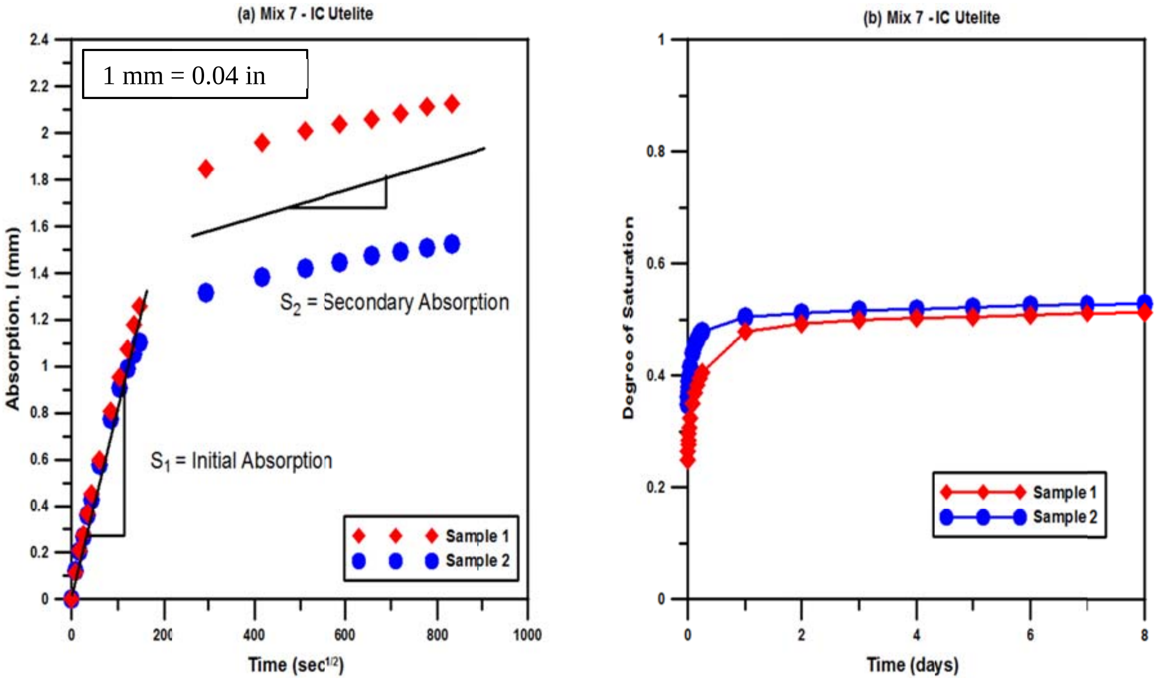


Figure 8.7: (a) Water absorption and (b) change in DOS for Mixture 7 – IC Utelite

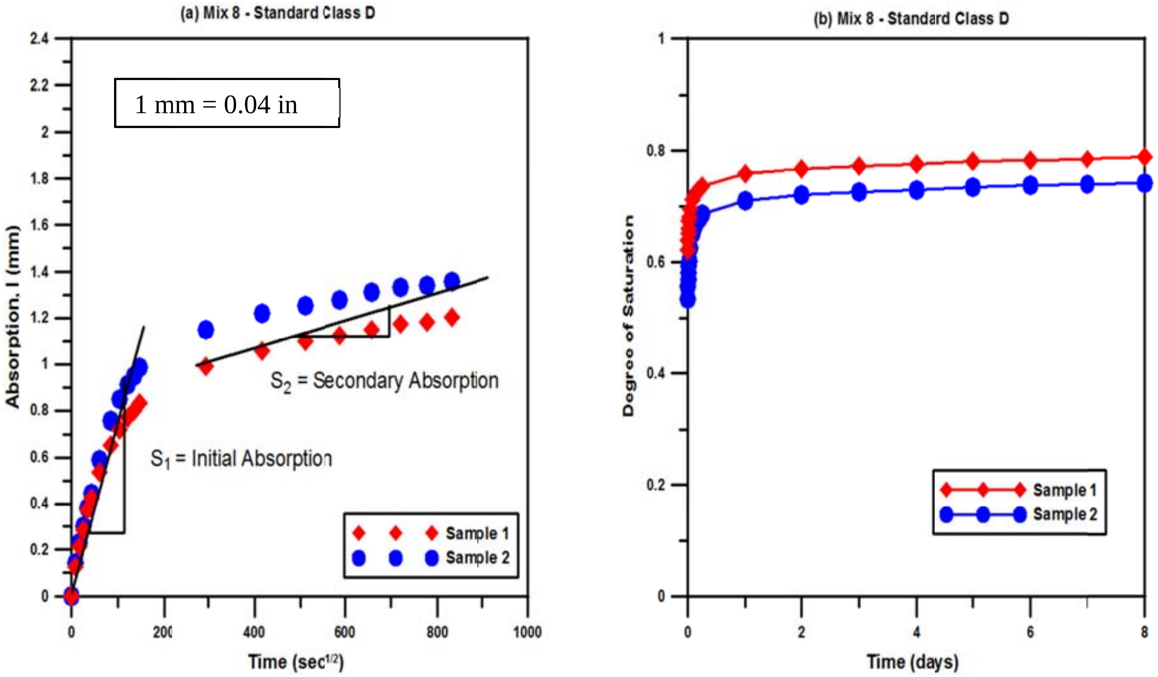


Figure 8.8: (a) Water absorption and (b) change in DOS for Mixture 8 – Standard Class D

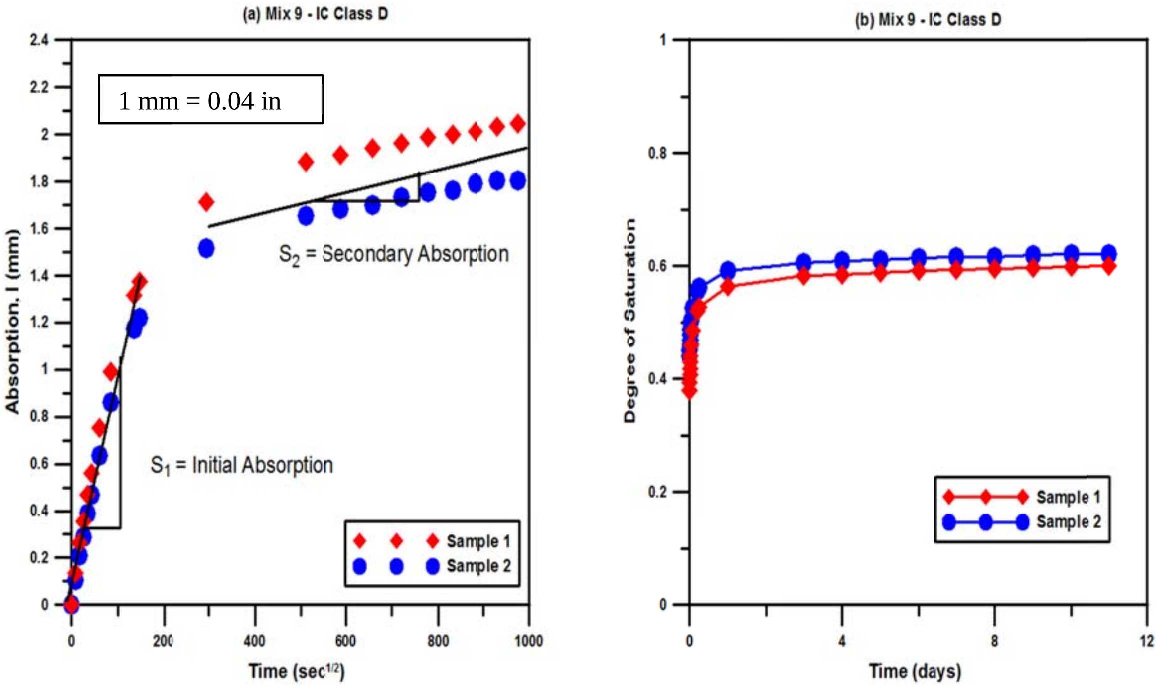


Figure 8.9: (a) Water absorption and (b) change in DOS for Mixture 9 – IC Class D

Table 8.4: Tabulated values for the initial and secondary absorption rates, 8-day depth of water penetration (I, mm), and the initial and 8-day DOS of the optimized mixtures

Mixture ID	**S_1 (mm/sec$^{1/2}$)**	**S_2 (mm/sec$^{1/2}$)**	**$I_{8\text{-day}}$ (mm)**	**Degree of Saturation (%)**	
				Initial	**8-day**
Mix 6: IC Buildex	6.44E-03	4.82E-04	1.69	27%	47%
Mix 7: IC Utelite	7.94E-03	4.32E-04	1.82	30%	52%
Mix 8: Standard Class D	5.90E-03	3.82E-04	1.28	58%	77%
Mix 9: IC Class D	8.74E-03	4.33E-04	1.93	41%	61%

1 mm = 0.04 in

8.4 Summary and Conclusions

This chapter investigated the transport properties of both standard and internally cured Colorado DOT Class H and D mixtures. The transport properties presented consist of ionic transport and water absorption for each of the nine mixtures. Results from this chapter can be summarized as follows:

- Internally cured concrete reduces the chloride diffusion coefficient and tortuosity up to 67% compared to standard mixtures.
- The reduced diffusion and tortuosity is attributed to increased hydration from internal curing and is beneficial even though the volume of porosity is increases.
- Permeability is decreased for Class H mixture for the “recommended IC” (i.e., LWA used to replace the water lost to chemical shrinkage).
- Internally cured mixtures are comparable to standard mixtures as it relates to water absorption. Higher values are attributed to exposed (and empty) LWA particles that reabsorb water during this test.
- All mixtures are below what is considered the ‘critical DOS’ after eight days of absorption testing.

CHAPTER 9. SUMMARY AND RECOMMENDATIONS

9.1 Introduction

Internally cured concrete has been rapidly emerging over the last decade as an effective way to improve the performance of concrete. IC holds promise for producing concrete with an increased resistance to early-age cracking and enhanced durability (Bentz and Weiss, 2011). The technique of IC has recently been studied and used in several field applications. As of 2010, hundreds of thousands of cubic meters of concrete containing pre-wetted lightweight aggregate (LWA) for the use of internal curing have been placed throughout the United States (Bentz and Weiss, 2011).

Internal curing is a simple a way to effectively cure concrete. Proper internal curing replaces water lost due to chemical shrinkage and supplies water that is necessary to relieve stress buildup in self-desiccation; typically via pre-wetted LWAs.

The idea of internal curing was originally promoted to reduce autogenous shrinkage and autogenous shrinkage cracking (Weber and Reinhardt, 1996; Bentz and Snyder, 1999; Jensen and Hansen, 2001; Kovler and Jensen, 2005; Radlinska et al., 2007; RILEM, 2007; Lopez et al., 2008). Autogenous shrinkage is a phenomenon caused by chemical shrinkage, independent of drying. However, the benefits go well beyond the reduction of autogenous shrinkage.

9.2 Summary of Experimental Results

Chapter 2 described the mixtures that were to be used in this study and introduced the materials and material suppliers. Chapter 3 evaluated the material properties that were to be used in the mixture designs. The absorption and desorption properties of LWAs were presented, as well as methods for obtaining these. As a rule of thumb, an efficient LWA is one that can desorb as least 85% of the absorbed water at a relative humidity of 94%, per ASTM C1761 (2012). Obtaining the correct absorption and moisture contents in the LWA particles are an essential part of creating quality IC mixtures. Two methods were discussed, however it is the opinion of the authors that the centrifuge method (Miller et al., 2013) is the most consistent method for obtaining moisture content. Chapter 4 presented the mixing techniques and mixture proportions that were used during this study.

Chapter 5 investigated the fresh and mechanical properties of mixtures used in this study. Values for slump, air content via the pressure and volumetric method, and unit weight were reported for the fresh properties. Internally cured mixtures do not have a significant impact on the slump. While the volumetric and pressure method vary in results, this does not prohibit the use of the pressure method. The pressure method is generally the preferred method for field application and has been specified in states that use internal curing. ASTM C231 (2010) specifies that this method “is not applicable to concrete made with lightweight aggregates.” However, the recommended IC mixture (i.e., where enough water is supplied by fine LWA to replace the water lost to chemical shrinkage) only replaces a fraction of the normal-weight aggregate (about 20%), leaving the majority of the volume is still occupied by normal-weight aggregate. For the recommended IC mixtures the unit weight is not significantly altered, the most being mixture 6 with a decrease by 8%. Mixture 2 and 7 only change by 1% and 3%, respectively.

Values for compressive strength and elastic modulus were reported at 28 and 56 days for the mechanical properties. In compression, the IC mixtures performed just as well and in some cases better (by about 10%) than the standard mixture and were all above the values specified by Colorado DOT specification. The increase in compressive strength is attributed to the increased hydration caused through internal curing. These findings are consistent with work done by Golias (Golias et al., 2012). All IC mixtures showed a reduction in the modulus of elasticity (about 10 – 20%), which is attributed to adding a material that has reduced stiffness (i.e., LWA). This will actually benefit mixtures in reducing shrinkage cracking, as the modulus at the interface of the aggregate and paste are more similar and do not create a large restraint, which would consequently generate large stresses.

Chapter 6 investigated the cyclic freezing and thawing behavior of the mixtures used in this study. Specifically each mixtures resistance to scaling and rapid freeze-thaw action. The findings provide an insight to the freezing and thawing durability of IC concretes. These results of ASTM C666 (2003) show that properly air entrained, internally cured concrete with a reasonable w/c (approximately 0.48 or less) have no issues in resisting cyclic freeze-thaw action. However, “excessively” internally cured mixtures, i.e., mixtures that have more pre-wetted LWA than is required to replace water lost due to chemical shrinkage for sealed concrete, perform poorly in freeze-thaw environments. These mixtures, mixtures 3 and 5, show up to an 86% reduction in durability from the standard Class H mixture with an average of a 37.5% reduction in durability between the two mixtures. Scaling results showed that internally cured mixtures do not perform any worse than the standard mixtures.

Chapter 7 investigated the shrinkage properties of the mixtures used in this study. Specifically autogenous shrinkage, restrained shrinkage cracking, and free shrinkage in a 50% relative humidity (RH) drying condition. The chemical shrinkage should be investigated if any different cementitious material composition is used. Internally cured mixtures prevent autogenous shrinkage and cause expansion (or swelling) in a sealed system. This expansion will eventually relax out over time and hydration of the cement subsides. Restrained shrinkage showed that IC concrete reduced the residual stress buildup in the material, however this was not as apparent in these “higher” w/c mixtures as it would be when comparing a lower w/c with the IC counterpart. For example little difference was noted for the Class D mixture, in which a 0.45 w/c was used. Internally cured mixtures show improved drying shrinkage performance, since water is present in the matrix to continue hydration as the surface dries. However, one should realize the shortcomings of performing only the drying test, as the test does not account early age shrinkage.

Chapter 8 investigated the fluid transport properties of the mixtures used in this study. The transport properties presented consist of porosity determination, water absorption, and ionic species transport for each mixture. Internally cured concrete reduces the chloride diffusion coefficient and tortuosity up to 67% compared to standard mixtures, which is attributed to increased hydration. Permeability is also decreased when the recommended IC mixture is used. Sorption properties are comparable from recommended IC mixtures (except for the case of the Class D mixture, which showed improved sorption properties for IC mixture) and all mixtures were below the critical degree of saturation for freezing and thawing after eight days of testing.

In summary, this study has demonstrated that benefits of properly internally cured concrete include:

- Similar or increased compressive strength
- Decreased elastic modulus
- Similar resistance to freeze-thaw action
- Reduced early age stress formation
- Reduced ion diffusion
- Similar fluid absorption

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