

Thoughts on the Service Life of Internally Cured Concrete Considering ASR and FT

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Abstract

Internal curing has been proven as a solution to reduce early-age shrinkage and related cracking in concrete. Internal curing can reduce the risk of built in stress, cracking, and curling in concrete pavements. However, the benefits of internal curing go beyond just shrinkage and cracking mitigation. Research by the author's has shown the incorporation of fine lightweight aggregate-FLWA can significantly reduce the risk of deleterious alkali-silica reaction. When the FLWA replaces a reactive aggregate a dilution effect occurs, but other benefits also exist. The curing provided by internal curing can react a greater percentage of cementitious material allowing a reduction in cement and an increase in the amount of binder fillers thereby reducing the alkali loading of the mixture. Additionally, the internal curing was shown to reduce the pH of the internal concrete pore solution and led to a refinement of the interfacial transition zone, possibly due to a pozzolanic reaction. The FLWA provides a porous inclusion which appears to enable a reaction product, similar to ASR gel to form however with limited expansion.

Introduction

In the past 20 years research has focused on using pre-wetted lightweight aggregate into high performance concrete to serve as internal moisture reserves for internal curing¹⁻⁵. While the benefits of internal curing are well documented⁶, little information exists as to the benefits these types of aggregates may provide in terms of durability including resistance to alkali-silica reaction and freeze-thaw attack⁷.

Different types of LWAs suitable for internal curing are commercially available and are shown to vary based mainly on their absorption capacity^{8,9}. However, their chemical composition, density, surface texture and porosity/permeability are also important parameters to consider and may affect durability of concrete incorporating these materials¹⁰. There are two main types of LWAs: occurring naturally or produced by thermal treatment. The natural aggregates are usually ready to use and are sized by mechanical crushing, e.g. volcanic material. The aggregates produced by thermal treatment include: perlite, vermiculite, and expanded clay, shale, slag, and slate¹¹.

Alkali-silica reaction (ASR) is a term used to describe the reaction between alkali hydroxides in concrete pore solution and aggregates with amorphous or strained crystalline phases. Once the silica is liberated from the aggregate it can combine with alkalis to form an alkali-silica gel. This gel has a high affinity for water and when it imbibes water swelling can occur^{12,13}. This swelling leads to tensile force being exerted on the concrete matrix and if the

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tensile force overcomes the tensile capacity of the matrix, cracking will result. Mitigation of alkali-silica reaction is well known to be achieved through the use of supplementary cementitious materials as a replacement for a portion of the portland cement in concrete¹⁴⁻¹⁹. Chemical admixtures, mainly lithium nitrate, can also be used to mitigate alkali-silica reaction in concrete²⁰⁻²². Using traditional supplementary cementing materials (SCMs) can be a challenge due to the regional availability of such materials. Further, as the use of fly ash in concrete comes under question in the coming years it is important to establish other sources of materials that may mitigate or be part of a solution to ensure intended service-life of concrete structures, in particular concrete pavements.

The use of lightweight aggregate for ASR mitigation has not been fully explored. Further, only a few researchers have suggested mechanisms by which lightweight aggregate may provide a reduction in expansion and deleterious reactivity. This small number of researchers does not agree upon those mechanisms. The proposed mechanisms by which lightweight aggregate may reduce expansion include: dilution of reactive aggregates, pore solution dilution through additional supply of internal curing water, accommodation of formed gel into the porous lightweight aggregate, a refined interfacial transition zone and/or increased pozzolanic activity due to the inclusion of lightweight aggregate²³⁻²⁸.

Research Significance

The use of internal curing for shrinkage and cracking mitigation is well known. While the vast majority of previous work has examined the shrinkage and cracking of mixtures using internal curing it is important to understand their impact on other properties. The aim of this paper is to describe the impact of internal curing on two well-known durability issues: alkali-silica reaction and freeze-thaw attack. The paper will show that internal curing has the potential to reduce ASR damage and to have similar performance to conventional concrete in a freeze-thaw environment.

Methodology, Results and Discussion

Alkali-Silica Reaction

Two sources of fine lightweight aggregate (FLWA), expanded shale and expanded clay, were investigated to determine their ability to mitigate alkali-silica reaction with a known highly reactive fine aggregate (HR). The HR fine aggregate was a mixed mineralogy gravel with volcanics from Bend, Oregon.

ASTM C1260/1567 (the accelerated mortar bar method without/with mitigation options, respectively) and ASTM C1293 (the concrete prism test) were used to determine the efficacy of the two FLWA to mitigate ASR. In the ASTM C1260 test, four mortar bars measuring 25 x 25 x 285 mm were cast and cured at 100% RH and 23C for 24 hours. After 24 hours they were submerged in tap water and placed in an 80C oven for another 24 hours. After this (48 hours after casting) the bars were measured for initial length and transferred immediately to a 1 N NaOH solution, already at 80C. The bars were measured periodically over the course of 14 days and the expansion after 14 days of immersion in 1 N NaOH was compared to an expansion limit of 0.10%. For this test the control HR fine

aggregate was tested as well as mortar mixtures with replacements of 25, 50 and 100% expanded shale or expanded clay by volume for the HR fine aggregate. ASTM C 1293 was also used to determine the efficacy of the FLWA (expanded shale and clay) for mitigating alkali-silica reaction. In this test four prisms measuring 75 x 75 x 285 mm were cast and cured for 24 hours at 100% RH and 23C. The mixing proportions followed ASTM C 1293 and in this case a non-reactive coarse aggregate (verified by ASTM C1260 and C1293 to fall below both expansion limits at 14 days and 1 year, respectively) was combined with the HR fine aggregate. Replacements of the HR fine aggregate were made by 25 and 50% fine lightweight aggregate, by volume. The prisms were demolded after 24 hours and stored in a 100% relative humidity environment at 38C for a period of two years. Expansions were monitored to two years. For brevity only the one-year results are shown here.

Samples were taken from the ASTM C1293 prisms at various ages for analysis by scanning electron microscopy and pore solution composition determination. Results after 1 – year of testing will be conveyed herein.

Figure 1 shows the results of testing in ASTM C1260/1567.

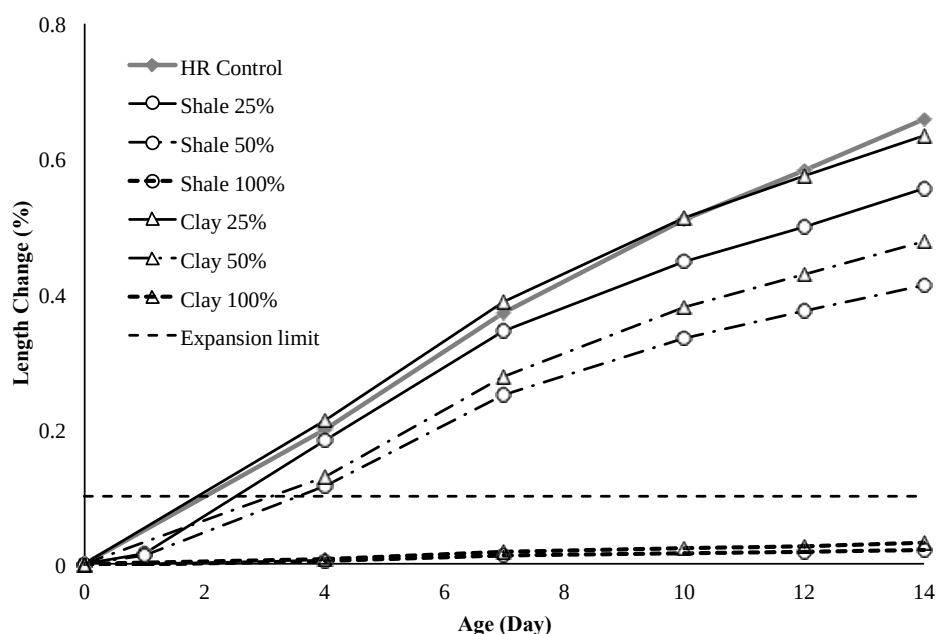


Figure 1: ASTM C1260 expansion of highly reactive control (HR) fine aggregate; highly reactive control fine aggregate with various replacement levels of expanded shale or clay and 100% expanded shale or clay fine aggregate

From Figure 1 it can be seen that the 50% replacement of HR fine aggregate by either expanded shale or expanded clay were the most effective in reducing the expansion over the HR control fine aggregate. While neither mixture provided complete mitigation below the expansion limit there was a significant reduction in expansion, near 50% for the mixture incorporating the 50% expanded shale. Both the expanded shale and clay, when tested at 100% (or as the sole aggregate in the mortar bar) both exhibited expansion well below the 0.10% expansion limit at 14 days.

Figure 2 shows the results of ASTM C1293 testing for the HR fine aggregate and the two FLWA samples tested in this study.

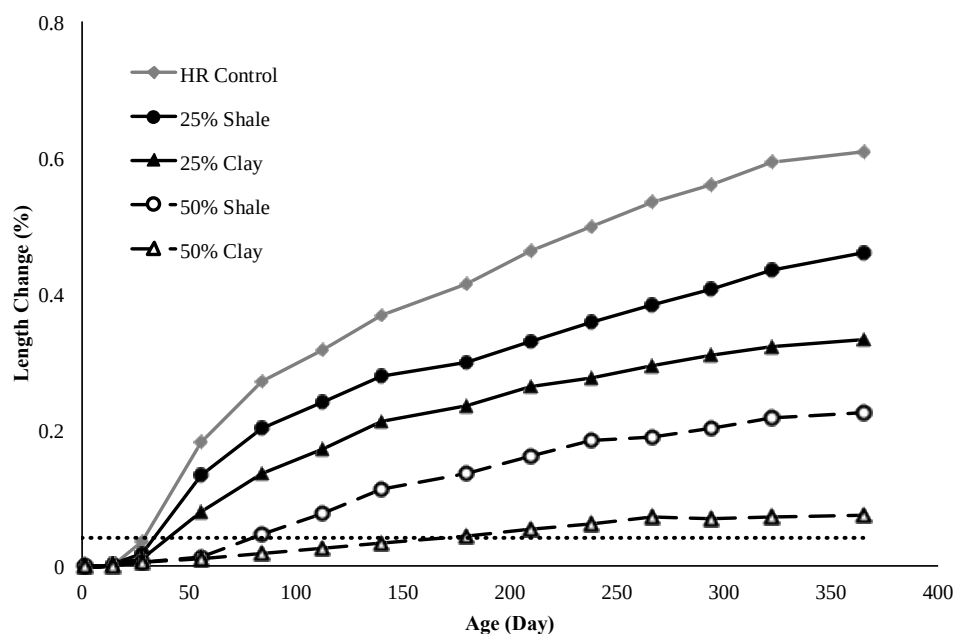


Figure 2: ASTM C1293 expansion of highly reactive control (HR) fine aggregate and highly reactive control fine aggregate with either 25 or 50% replacement of expanded shale or clay fine lightweight aggregate

At an age of 365 days (1 year) all mixtures incorporating either shale or clay showed significant reduction in expansion compared to the HR control fine aggregate. At the same replacement level, the expanded clay showed greater ability to reduce expansion in the ASTM C1293 test. At a 50% replacement of clay the expansion was reduced the most effectively to just above the 0.04% expansion limit. While this would not pass the test on its own, it is a significant reduction in expansion from the control of approximately 87% reduction in expansion. While this would not complete control the reaction to below the 0.04% expansion limit, there is a possibility that combining a FLWA with a supplementary cementing material or a chemical admixture such as lithium nitrate could provide a synergistic benefit to mitigate ASR relate expansion to below the expansion limit in the ASTM C 1293 test.

To further understand the mechanisms by which FLWA may mitigate ASR an extensive study was undertaken to evaluate dissolution characteristics, investigate scanning electron microscopy images with energy dispersive x-ray and pore solution analysis. Only preliminary results from this work are included herein. Figure 3 (HR control) and Figure 4 (HR control with 50% expanded clay replacement) show SEM images of the concrete prisms taken from the ASTM C1293 after 365 days of exposure (e.g. corresponding to the latest expansion in Figure 2).

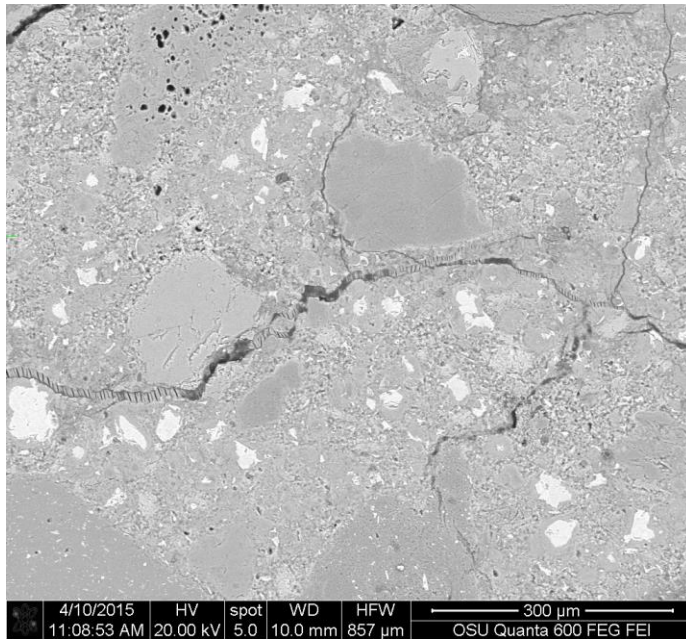


Figure 3: SEM image of highly reactive control after 365 days of ASTM C1293 exposure

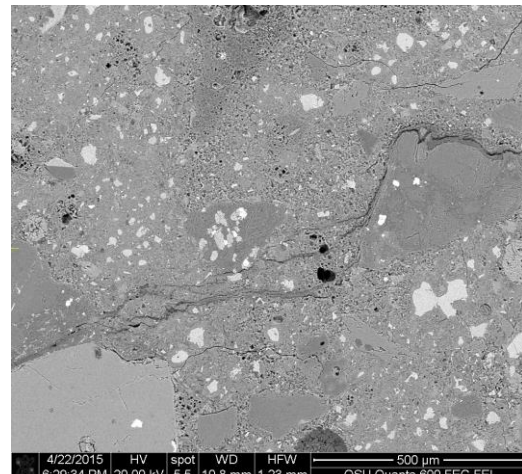
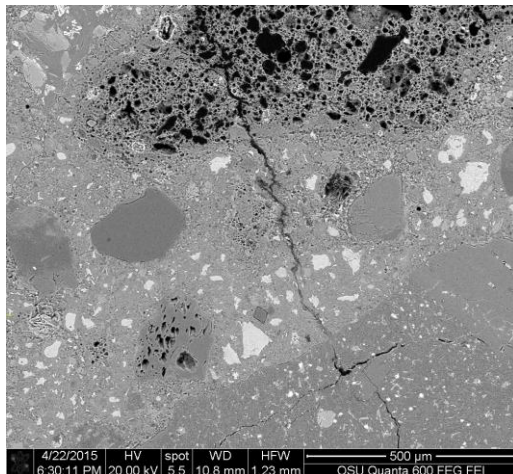


Figure 4a and b: SEM image of highly reactive control with 50% replacement of expanded clay fine aggregate after 365 days of ASTM C 1293 exposure

In Figure 3 extensive microcracking was seen within the cement paste and around the HR fine aggregates. Some dehydrated ASR gel was also observed in the wide crack in the upper left hand portion of the image frame. This level of damage is consistent with the high level of expansion (0.6%) after 1 year of exposure to 100% RH and 38C. In Figure 4 the microstructure was shown to be in a more sound state. There is some microcracking evident although the extent of the cracking and width of cracks was much smaller compared to the cracking seen in Figure 4. A porous FLWA, approximately 500 μm across, can be seen in the upper 1/3 of the image for Figure 4a. A reaction rim with partial infilling of the porous FLWA was observed. This infilled reaction product was observed by SEM-EDX and was shown to have a composition somewhere between C-S-H and alkali-silica gel. The expansive nature of this reaction product and potential link to damaging ASR is still under question and is being analyzed as part of this larger study. Pore solution analysis also showed a lower pH

pore solution for mixture incorporating 50% expanded clay compared to the HR control aggregate²⁹.

Freeze-thaw Study

A study was performed that investigated nine concrete mixtures (Jones et al. 2013a,b), typical of those used for concrete paving and bridge decks in Colorado (CoDOT Construction Specification Section 601, 2011a)³⁰⁻³³. A description of the mixtures is given in Table 1 and the mixture proportions are given in Table 2 and Table 3. The Colorado Class H concretes have a water/cementitious material ratio (w/c) of 0.42 with a fixed cementitious material content of 338 kg/m³ and 20 percent replacement of fly ash, by mass. The mixtures consist of 55% 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.

An air entraining admixture was used, MB-AE 90 by BASF (recommend dosage of 16 – 260 mL/100 kg, to obtain this desired air content range. A water reducing admixture, Glenium 3030 by BASF (recommend dosage for mid-range use of 195 – 390 mL/100 kg, was added to the mixtures until desirable lab workability was achieved, taking caution to avoid aggregate-paste segregation.

The Colorado Class D mixtures, standard and internally cured, have a w/c of 0.45. The mixtures were designed to represent a standard concrete mixture (mixture 1 and 8 for class H and D respectively), a typical internally cured mixture where the volume of internal curing water was equal to that of the total chemical shrinkage (mixture 2, 6, 7, 9 for class H mixtures with three different fine aggregate sources and a class D mixture respectively), mixture 4 and 5 explore the use of coarse LWA at two different loading levels and mixture 3 explores the use of fine LWA with twice the typical dose of LWA. The absorption (and oven dry specific gravity) of the LWA at 72 hr. was 18.5% (1.85), 18.7% (1.65) and 19.9% (1.87) for the shale LWA produced by TXI Boulder, Buildex (a shale from Kansas) and Utelite (a shale from Utah) fine aggregate and 17.5% (1.74) for the coarse LWA manufactured by TXI^{8, 9}.

Table 1: Description of mixtures used in this study

ID	Mixture Description
Mixture 1	Standard Class H Colorado Department of Transportation bridge deck mixture
Mixture 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)
Mixture 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)
Mixture 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)
Mixture 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)

Mixture 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)
Mixture 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)
Mixture 8	Standard Class D Colorado Department of Transportation bridge deck mixture
Mixture 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)

Table 2: Class H Mixture Proportions

Class H Standard Mixture		
<i>Note: Agg in SSD Condition</i>		
	Amount (kg/m ³)	Amount (lbs/yd ³)
Cement	270	456
Fly Ash	68	114
Water	142	239
FA	885	1493
CA	1091	1840

Table 3: Class D mixture proportions

Class D Standard Mixture		
<i>Note: Agg in SSD Condition</i>		
	Amount (kg/m ³)	Amount (lbs/yd ³)
Cement	303	510
Fly Ash	76	128
Water	170	287
FA	835	1409
CA	1029	1736

Mixing was performed in accordance with ASTM C192 (2007). The concrete was made using a dual action, 85L 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, LWA's were prepared according to ASTM C1761 (2012), with a soaking time of 72 ± 4 hours. 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 (FA and CA respectively) were first combined in a “buttered” mixer, adding a portion of the batch water to control dust and to 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.

Since the freeze-thaw durability of internally cured mixtures was the primary focus of the mixtures evaluated in this study the air content of the mixtures was measured for each mixture. 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. Each mixture was within the range of 5-8%, as prescribed by Colorado DOT Specification Section 601 (Colorado Department of Transportation, 2011a).

Fresh Air Assessment

The fresh air content was measured using two procedures, the volumetric air content and the air content determined from the pressure method. Results from these two tests are provided in Table 4.

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 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 of water was added followed by 1 L 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 tilted 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 a 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.

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 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.

The volume of air reported using the volumetric method and the pressure method were similar for the conventionally internally cured mixtures. This implies that either approach can be reliably used in the field for quality control and performance testing.

Table 4: Air Entrainment and Fresh Air For the Freeze-Thaw Samples

Mixture:	AE (fl oz/cwt)	Air_{Pres.} (%)	Air_{Vol.} (%)
Mixture 1: Standard Class H	0.2	5.80%	5.25%
Mixture 2: TXI fine LWA (CS)	0.2	5.90%	4.75%
Mixture 3: TXI fine LWA double dose	0.3	5.00%	5.00%
Mixture 4: TXI coarse LWA (CS)	0.4	6.20%	5.75%
Mixture 5: TXI coarse LWA (100% repl)	0.4	7.00%	5.75%
Mixture 6: Buildex fine LWA (CS)	0.3	7.9%	6.5%
Mixture 7: IC Utelite fine LWA (CS)	0.3	6.8%	6.8%
Mixture: Class D	0.3	6.0%	5.8%
Mixture 9: TXI fine LWA (CS) – Class D	0.2	6.1%	5.8%

Freeze – Thaw Performance

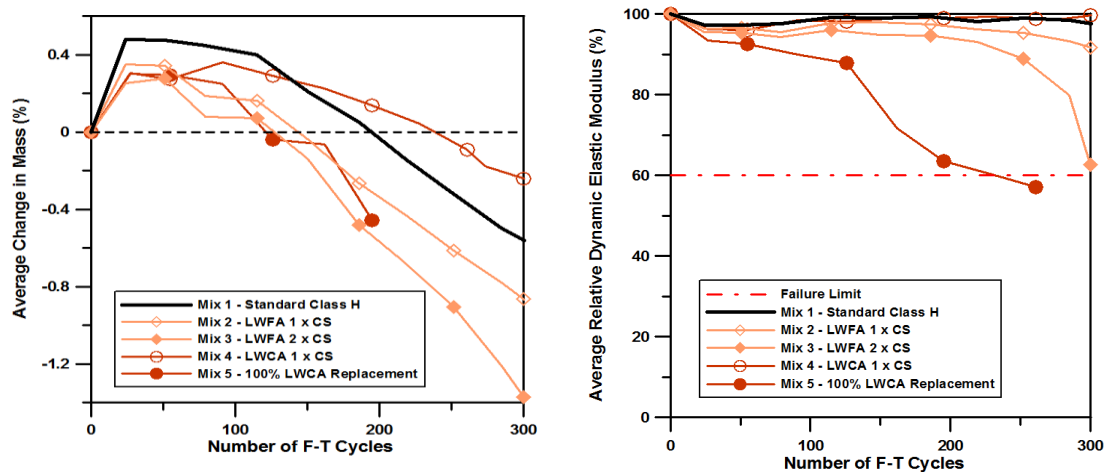
The rapid freezing and thawing durability of each mixture was determined in accordance with ASTM C666 (2003, reapproved 2008). Sets of three 100 mm wide by 75 mm tall by 400 mm long samples were cast for each mixture. The specimens were cast in two lifts, being vibrated and rodded 25 times after each 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 $23 \pm 1^\circ\text{C}$ for a 14-day curing period.

The freeze-thaw durability of each mixture was determined in accordance with ASTM C666/C666M – 03(2008), Procedure A. After the initial mass and frequency measurements were determined, the specimens were placed in a pan with water, such that all faces were completely surrounded by not less than 1 mm nor more than 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, which consist of alternately lowering the temperature of the specimens from 4 to -18°C and raising it from -18 to 4°C in $4 \frac{1}{2} \pm \frac{1}{2}$ hour. Specimens were removed at the desired thaw temperature and tested approximately every 36 cycles, until a total of 300 cycles was reached, or until the relative dynamic modulus of elasticity reached 60% of the initial modulus.

The results of cyclic freezing and thawing of internally cured concrete mixtures are presented in Figure FT5. The average durability index of each mixture is plotted as a function of the number of freeze-thaw cycles (Figure 5 a, c). In addition, the mass of the samples is plotted as a function of the number of freeze-thaw cycles (Figure 5 b,d).

Two mixtures immediately stand out as poor performers in cyclic freezing and thawing (Mixture 3 and Mixture 5). Mixture 3 is the sample that contains double the internal curing water. Mixture 5 also contains additional internal curing water as 100% aggregate replacement was used to get close to an appropriate aggregate spacing. These two mixtures show a 36 and 40% loss in durability, respectively, when compared to the equivalent, Plain – Deck mixture. This reduction in the durability factor can be directly attributed to excess, unused, water that remains inside the aggregate and concrete matrix, filling in void space and increasing the degree of saturation in the concrete and lightweight aggregate.

If the typical amount of IC water is supplied (i.e., enough to replace only in the volume of chemical shrinkage) the durability factor test results are statistically similar to that of the standard non-internally cured mixtures. None of the mixtures produced using the three different fine LWA demonstrated no increased susceptibility to freeze-thaw damage. These mixtures had a durability factor of 96% and as such the performance of the internally cured structural mixture is consistent with the non-internally cured mixtures. Therefore, if internally cured mixtures are used where a portion of the fine NWA is replaced with pre-wetted LWA cyclic freeze-thaw durability is not an issue when a w/c of 0.42 and 0.45 are used provided the mixture has sufficient air content.



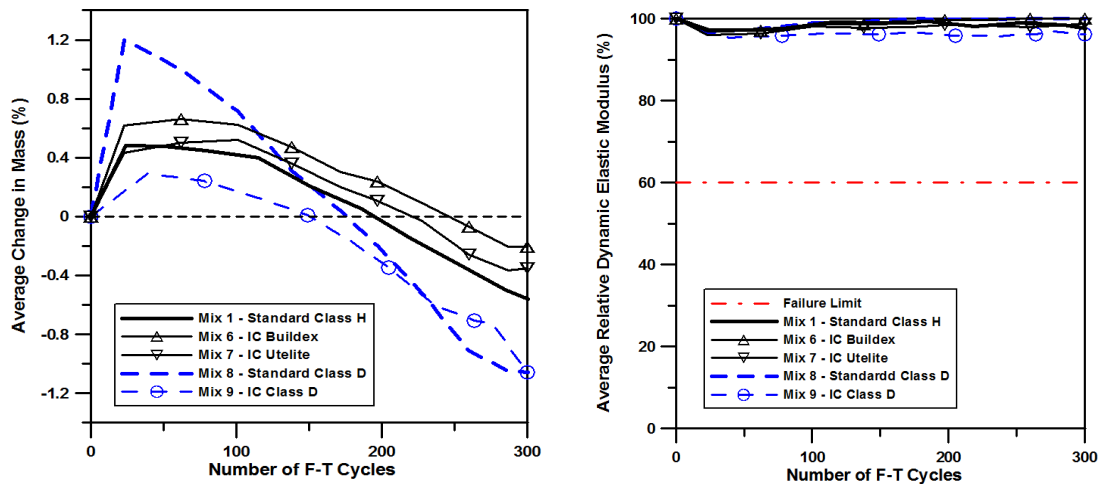


Figure 5: Freeze-thaw performance of the concrete mixtures: a and c) mass measurement; b and d) average dynamic elastic modulus measurements.

Conclusions

The replacement of fine lightweight aggregate for normal weight alkali-silica reactive aggregate was shown to reduce expansion over a highly reactive control aggregate in accelerated laboratory testing. Both an expanded shale and expanded clay were investigated. The expanded clay showed the greatest efficiency in reducing deleterious alkali-silica related expansion. At a 50% replacement of expanded clay the expansion of concrete prisms was reduced to just above the 0.04% expansion limit after 1 year of exposure. While the use of 50% expanded clay did not completely control the expansion of alkali –silica reaction the 87% reduction in expansion over the control represents a significant benefit of using internal curing toward achieving durable concrete mixtures. Further work should be undertaken to determine the synergistic effects of FLWA with supplementary cementitious materials for ASR mitigation. There is potential for a holistic solution to ASR that will also provided other benefits for long lasting concrete.

It was determined that the volume of air reported using the volumetric method and the pressure method were similar for the conventionally internally cured mixtures. This implies that either approach can be used in the field for quality control and performance testing. The freeze-thaw durability of both standard and internally cured Colorado DOT Class H and D mixtures was evaluated. The freeze-thaw was conducted using a testing protocol that was close to a “worst case scenario” situation, i.e. specimens were directly placed into the testing chamber from a sealed condition. If the typical amount of IC water is supplied (i.e., enough to replace only in the volume of chemical shrinkage) the durability factor test results are statistically similar to that of the standard non-internally cured mixtures. None of the mixtures produced using the three different fine LWA demonstrated no increased susceptibility to freeze-thaw damage. This is done to clearly identify which mixtures perform poorly in freeze-thaw conditions, not to replicate field conditions. It was observed that internally cured mixtures that contained excessive LWA (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 as well in freeze-thaw environments. The 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.

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