ERDC/GSL TR-19-11

Geotechnical and Structures Laboratory

US Army Corps of Engineers®
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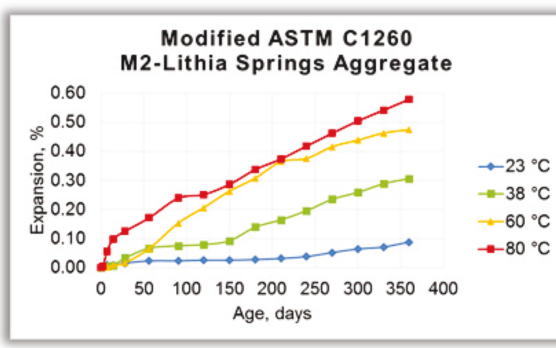
Monica A. Ramsey, Stephanie G. Wood, and Robert D. Moser

March 2019



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Under Project KD3B55, "Predictive Service Life Modeling for Aging Navigation Structures"

Abstract

The objective of this study was to develop methods to sample and test residual alkali-silica reaction-induced expansion capacity of in-situ concrete using cores tested in accelerated environments. The effect of alkali-silica reaction on the mechanical properties of concrete was also investigated in order to more accurately predict the remaining service life of existing concrete structures. Residual expansion measurements were taken up to 12 months on cores drilled from large concrete blocks produced with two different reactive aggregates and stored in various exposure conditions at different temperatures. The three exposure conditions were sealed, stored in NaOH solution, and stored over water. The four temperatures were 23, 38, 60, and 80^{0}C. Compressive strength, splitting tensile strength, and modulus of elasticity were measured for cylinders immersed in NaOH at 80°C up to 56 days to generate correlations between ASR damage and mechanical properties. For unboosted cores, the 80°C modified conditioning regime appeared to be the most effective in producing significant residual expansion in a short period of time. Late-age conditioning had essentially no impact on the expansion of cores at one year. Modulus of elasticity was influenced most and was more accurately captured by delaying conditioning.

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Preface

This study was conducted for the U.S. Army Engineer Research and Development Center (ERDC) Civil Works Navigation Systems research and development program under Project KD3B55, "Predictive Service Life Modeling for Aging Navigation Structures." The technical monitor was Dr. Robert D. Moser.

The work was performed by the Concrete and Materials Branch (CMB) and the Research Group (RG) of the Engineering Systems and Materials Division (ESMD), The U.S. Army Engineer Research and Development Center- Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Mr. Christopher M. Moore was Chief, CMB; Mr. Jeffrey Averett was Acting Chief, ESMD; and Mr. R. Nicholas Boone was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of the ERDC-GSL was Mr. Charles W. Ertle, and the Director was Mr. Bartley P. Durst.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square inches	6.4516 E-04	square meters
yards	0.9144	meters

1 Introduction

1.1 Background

The U.S. Army Corps of Engineers (USACE) has aging navigation infrastructure, and limited funding has been allocated for maintenance and repair of these structures. In order to accurately budget for repair and/or replacement in the future, an estimate of the expected useful life of these structures is needed. Currently, minimal guidance is available for determining the estimated useful lifespan of structures, which often leads to inaccurate estimates based solely on expert elicitation.

Some literature exists on service life modeling of reinforced concrete structures subjected to corrosion. However, the impacts of other issues that often negatively affect the performance of concrete structures, such as alkali-silica reaction (ASR), freeze/thaw cycling, and carbonation, on the expected useful service life are not well understood. Thus, historical data as well as new data obtained by procuring and analyzing field samples of structures affected by AAR, freeze/thaw cycling, and/or carbonation were compiled and used to create a framework for how to approach these problems. The residual expansion potential is a valuable tool to assess the further development of ASR in a structure.

1.2 Objective

The objective of this research was to determine if modified laboratory test methods developed to measure residual expansions caused by ASR to assess in-situ concrete condition and expansion capacity in existing infrastructure in addition to the mechanical property tests could be used to determine the degree of structural damage of the affected concrete members.

This would be part of a future comprehensive service life modeling tool that can provide an accurate estimate for the expected useful service life of a structure based on various inputs, e.g., climate data, region, chemical environment, mineralogy of materials, etc., taking into account ASR and freeze/thaw induced damage in aging navigation structures. For existing structures, these models are informed by field forensic investigations and laboratory testing.

The project directly benefits USACE by providing a reliable, accurate tool to predict the useful service life of aging concrete structures. This will in turn provide better data for budgeting decisions and reduce the amount of unpredicted infrastructure repair and/or replacement needs. In addition, the procedures used for service life modeling of existing infrastructure can be applied for new construction.

1.3 Approach

A detailed literature review was performed to determine the project scope, and input was obtained from various experts to help define the desired mechanisms and capabilities of the service life model to be developed. Expert elicitation was obtained from academia as well as collaborators at the U.S. Bureau of Reclamation, USACE Inland Navigation Design Center, and USACE Risk Management Center. In addition, current approaches to service life modeling for various types of concrete deterioration were documented. Some of these, such as corrosion of steel in concrete, can be directly leveraged for development of USACE-specific guidance.

Field samples were obtained from concrete structures of various ages and localities showing various levels of distress due to AAR, freeze/thaw cycling, and/or carbonation. This required multiple site visits to inspect deteriorated structures and collect samples.

Simple, accurate, rapid test methods were identified and developed to analyze the samples obtained from the field and generate the data needed for service life modeling. Alkali-silica reaction testing required a fundamental understanding of damage mechanisms in the field through understanding of mineralogy and exposure conditions. Accelerated test methods typically used for aggregate evaluation prior to construction were modified to predict future deterioration in concrete extracted from existing structures, and the results of these tests were calibrated against structures that have historical monitoring data available. Similar approaches were used to study other forms of deterioration. This extensive task leveraged previous research and developed standard test methods that can be implemented in a USACE-specific framework for forensic evaluation of existing structures and design of new structures.

The data from analysis of the field samples were compiled and used to develop a service life model for concrete structures that accounts for ASR, freeze/thaw cycling, and carbonation. Simple modeling approaches that utilize simplified structural geometries, e.g., 1D deterioration processes, were developed initially. These methods can be used for conservative estimation of future deterioration. Potential for more complex applications of these models using two-dimensional (2-D) and three-dimensional (3-D) multiphysics finite element formulations, e.g., use of COMSOL, Abaqus, etc., or other analysis techniques were also conceptualized. This work was the study of a follow-on work unit focused on implementation of these deterioration models into multiphysics structural modeling tools.

Case studies were performed to test the accuracy of the model; structures were analyzed according to the procedure described here, and results of the model were compared to historical data. These included samples produced using known materials that have comparable lock term field performance data such as historically significant aggregates, e.g., Jobe, Las Placitas, Spratt, and Sudbury, that also have corresponding field exposure blocks that have been monitored for decades. Structures that have had long-term monitoring, e.g., Chickamauga L&D and Mactaquac Dam, in place were also used as test beds to calibrate deterioration models based on field performance.

A framework was developed describing how to approach the estimation of useful life for a concrete structure, and this framework will be used to produce guidelines in the form of technical reports and/or engineering technical letters. These publications focus on initial field forensic investigations and supporting laboratory techniques, identification of modes of deterioration, recommendations for tests to perform, and procedures for fitting to computations and closed-form-solution models for deterioration.

2 Literature Review

2.1 Residual expansion

Very little is known about the service life expectancy of concrete structures affected by alkali-aggregate reaction (AAR). In-situ monitoring of concrete structures exhibiting AAR damage is the best way to assess current expansion, but it is costly and may take several years to obtain data. Periodic measurements of residual expansions under laboratory conditions can assess the future behavior of ASR-affected structures in a more cost efficient and timely manner, but there are many differing research opinions on relevant test methods.

The most common laboratory tests for expansion-based measurements of potential AAR are found in ASTM C1293 Concrete Prism Test (CPT) and ASTM C1260 Accelerated Mortar Bar Test (AMBT). The Microbar Test (MBT) is a non-standardized test that follows a similar protocol to the AMBT except bars of different lengths, cross-sectional areas, aggregate gradations, and mixture proportions. Of the literature reviewed, the MBT appeared to be the least favorable test method due to moderate to no correlation between the MBT and CPT (Lu et al. 2008; Leemann and Merz 2013). Other non-standardized test methods developed include measuring residual expansion in cores extracted from either existing concrete structures damaged by AAR (Merz and Leemann 2013) or from realistic laboratory concrete specimens designed to replicate potential field AAR conditions (Multon et al. 2008). The expansion of the cores is measured using a length comparator by embedding extensometer studs on the face of each core.

A fundamental concept in the AAR risk assessment is the influence of the environmental conditions on the extracted cores. Variations in the testing parameters can include temperature, humidity, storage conditions, e.g., water or NaOH, sample conditioning, aggregate gradation, size of testing specimen, location of where core is extracted in a structure, amongst others. Common laboratory testing temperatures are 20 ^{0}C, 38 ^{0}C, 60 ^{0}C, and 80 ^{0}C. A consensus amongst researchers is the AAR reactions are accelerated by the relative humidity and temperature. In efforts to correlate the rate of residual expansion of laboratory tests to field concrete, Berube et al. (2002) suggested the use of a coefficient “Potential Rate of Expansion” (PRE) for application to various conditions. The coefficients take the following parameters into consideration: residual expansion in the laboratory (EXP), absolute degree of reactivity of aggregate (ABR), water-soluble alkali content (ALK), humidity effect (HUM), temperature effect (TEM), and the effect of reinforcement and other restraints (STR). The coefficient PRE is a qualitative indicator to approximate the potential rate of expansion caused by ASR to concrete structures in service. However, this method does not take in consideration other important information like the prediction of how much time the expansion will continue, the rates of expansion and deformation, the age of the structure, and modeling results.

Further research is needed to understand the relationship of the variations in testing parameters obtained with AAR-induced damage expansion accelerated tests. A hybrid of the methods described by Multon et al. (2008) and Merz and Leemann (2013) is the basis for the test matrix presented to assess the potential for ASR residual expansion in cores extracted from slabs of concrete materials exposed to various storage conditions and temperatures and the extent of damage on their mechanical properties.

2.2 Reduction in mechanical properties

Over time, ASR reduces the mechanical properties of affected concretes. This outcome has been demonstrated in a number of laboratory experiments involving accelerated conditions using relatively high temperatures and alkaline soak solutions to simulate the most severely exposed conditions in structures.

Giaccio et al. (2008) investigated the effect of ASR on mechanical properties for concretes made in accordance with ASTM C1293. Compressive strength and modulus of elasticity were measured on 100- x 200-mm and 150- x 300-mm cylinders and compared with companion prism expansions. Modulus of elasticity was more sensitive to ASR damage, exhibiting a more significant reduction than compressive strength for cylinders of both sizes. In fact, reactive specimens demonstrated an average 21 percent increase in compressive strength but an average 25 percent reduction in modulus of elasticity over time. Multon et al. (2005) reported a similar pattern for concrete specimens with the same alkali loading and similar laboratory conditioning.

3 Materials and Mixture Proportions

3.1 Materials

An ASTM C150 Type I/II portland cement with an equivalent alkali content (Na_2O_{eq}) of 0.54 percent was used in all mixtures. The chemical composition of the cement is provided in Table 1. The manufacturer's mill certification is provided in Appendix A.

Table 1. Chemical composition of portland cement used in testing.

Compound	Wt. %
SiO2	19.7
Al2O3	4.4
Fe2O3	3.2
CaO	64.5
MgO	2.3
SO3	3.5
Loss on ignition	2.5
Na_2O_{eq}	0.54

Two known reactive coarse aggregates (CA) and one known non-reactive fine aggregate (FA) were used in this study. One reactive coarse aggregate CA1 used to produce concrete M1 was a metapelite green schist, and the other reactive coarse aggregate CA2 used to produce concrete M2 was an intermediate to felsic. Both contain alkali-silica reactive constituents. X-ray diffraction analysis results for both CA1 and CA2 are provided in Appendix B.

3.2 Mixture proportions

All mixtures are denoted as M1 or M2, depending on which reactive coarse aggregate was used. M1 mixtures used the limestone aggregate, and M2 mixtures used the granite aggregate. Because of variations in mixture proportions and alkali loadings, mixtures are further denoted based on the experimental program in which they were used.

Aggregate gradations and mixture proportions for mortar bars and concrete prisms used in the standardized test methods followed guidance provided by ASTM C1260 and ASTM C1293. To create mortar bars for ASTM C1260, the reactive coarse aggregates were crushed into fine aggregate sizes. Mixtures used in the standardized test methods are denoted as M1S and M2S.

Four concrete mixtures were developed for measuring residual expansion and mechanical properties of ASR-affected concrete. Two mixtures were used to cast large blocks from which drilled cores were taken to measure residual expansion. The other two mixtures were used to cast cylinders to measure mechanical properties. Aggregate gradations and mixture proportions for all mixtures generally followed ASTM C1293 guidance. The coarse aggregates were graded as shown in Table 2 with a fine-to-coarse aggregate ratio of 40:60.

Table 2. Aggregate grading requirements in accordance with ASTM C1293.

Sieve Size		Mass Fraction	
Passing	Retained	Coarse	Intermediate
¾- in	½-in	1/3	-
½-in	3/8-in	1/3	½
3/8-in	#4	1/3	½

The block and cylinder mixture proportions were the same except that the cylinder mixtures incorporated sodium hydroxide (NaOH) in the mixing water to boost the Na_2O_{eq} to 1.25 percent. The unboosted block mixtures used for residual expansion are denoted as mixtures M1R and M2R (R denoting the use for residual expansion coring); the boosted cylinder mixtures for mechanical properties are denoted as mixtures M1M and M2M (M denoting the use for mechanical properties measurements). Table 3. provides the concrete mixture proportions for these materials.

Table 3. Concrete mixture proportions for measuring residual expansion and mechanical properties.

Material	Weight (lb/yd^3)			
	M1R	M2R	M1M	M2M
Type I/II cement	710	710	710	710
Limestone coarse aggregate	1976	-	1976	-
Granite coarse aggregate	-	1976	-	1976
Non-reactive FA	822	822	822	822
NaOH	-	-	6.48	6.48
Water/cement ratio	0.45			

4 Experimental Program

Expansion-based measurements of ASR damage are the most common test methods used to assess the ASR susceptibility of aggregates. Two standardized methods were used to test both mortar and concrete specimens, i.e., ASTM C1260 and ASTM C1293.

Residual expansion measurements were obtained for up to 12 months on cores drilled from blocks and stored in various exposure conditions at different temperatures. The three exposure conditions were sealed, modified ASTM C1260 conditions with cores submerged in 1 N NaOH, and modified ASTM C1293 conditions of 100 percent RH with cores stored over water. The four temperatures used were 23, 38, 60, and 80 ^{0}C.

All expansion measurements were performed using a digital Humboldt length change comparator accurate to 1.0 µm, as shown in Figure 1.

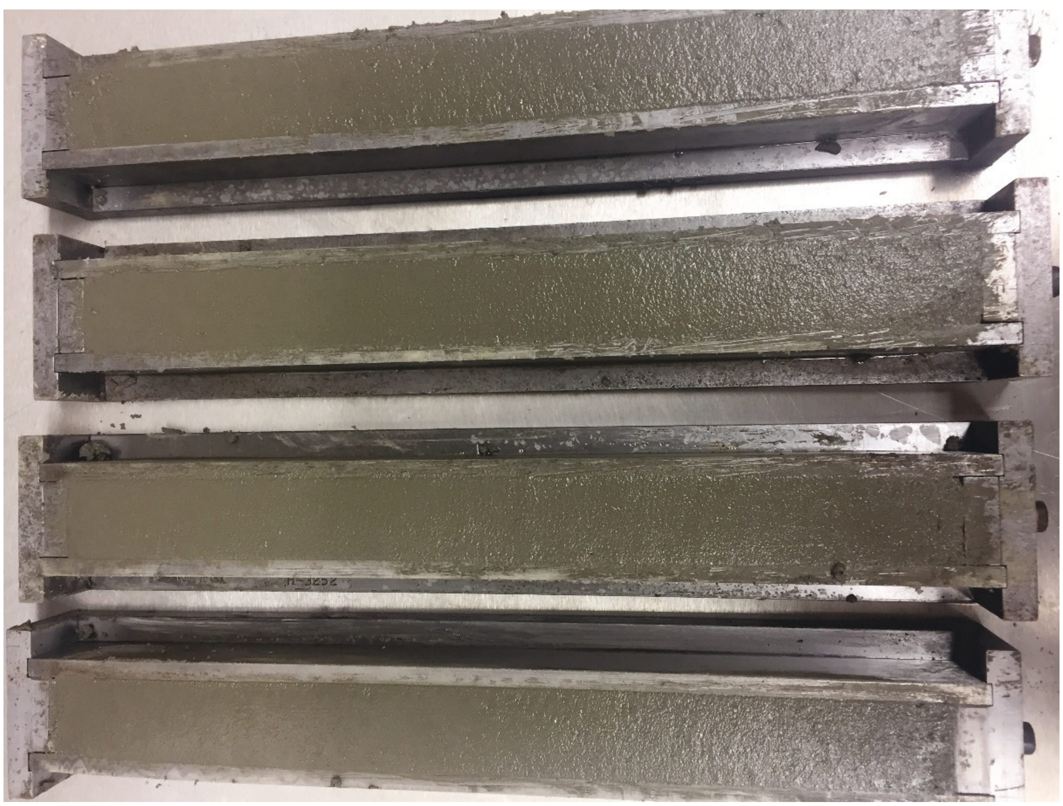
Figure 1. Humboldt length comparator used to measure length change.

Mechanical properties of compressive strength, modulus of elasticity, and splitting tensile at various ages were obtained to assess the correlation between ASR damage and reductions in mechanical properties.

4.1 Standardized test methods

The standard rapid expansion test, commonly referred to as the accelerated mortar bar test (AMBT), was performed according to the ASTM C1260, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). In this test, four 1- x 1- x 11.25-in. mortar bars (Figure 2) containing the fine proportion of the reactive aggregates used in this study were immersed in a 1 N NaOH solution at 80 °C for 28 days while expansions were measured. According to ASTM C1260, mortar bars exhibiting less than 0.1 percent expansion at 15 days are deemed innocuous, and mortar bars producing expansion greater than 0.2 percent are deemed reactive. Mortar bar expansions between 0.1 percent and 0.2 percent are deemed potentially reactive, and further testing on the aggregates is recommended.

Figure 2. Fresh mortar bars cast for ASTM C1260 testing.



The standard concrete prism test (CPT) was performed in accordance with the ASTM C1293, Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction. Three test specimens with dimensions 3- × 3- × 11.25-in. were cast using the mixture proportions described in the preceding chapter. Sodium hydroxide (NaOH) was added to the mixing water to boost the Na_2O_{eq} to 1.25 percent by mass of cement. Testing was conducted in a 38 °C storage environment with the prisms positioned on a rack above a 0.8-in. water layer within a sealed container lined with moist wicking paper to keep the RH > 95 percent, as shown in Figure 3. Expansion readings were recorded at 7, 28, and 56 days and at 3, 6, 9, and 12 months. According to ASTM C1293, an aggregate is deemed to be reactive, if concrete prism expansion at 1 year is greater than or equal to 0.04 percent.

Figure 3. Prisms in a sealed container at 38 ^{0}C and > 95% RH in accordance with ASTM C1293.

4.2 Simulated residual expansion testing

Two 24- x 24- x 12-in. blocks were cast in the laboratory from the concrete mixtures M1R and M2R. The blocks were allowed to cure for 7 days in the forms at 23 °C before formwork was removed and the blocks were cored.

Twenty-five 4- x 11.25-in. cores were taken from each concrete block for a total of 50 core specimens. The cores remained at approximately 23 °C in the laboratory while being instrumented with stainless steel gage studs for length change measurements. Pre-conditioning and conditioning of the cores are divided into two categories, i.e., early-age and late-age.

4.2.1 Early-age conditioning and testing

Three cores from each M1R and M2 mixture were tested under one of three environmental conditions, i.e., sealed, modified ASTM C1260, and modified ASTM C1293, at one of four temperatures, i.e., 23, 38, 60, and 80 °C. Prior to conditioning, these cores were stored in the laboratory at approximately 23 °C and ambient humidity for 28 days after casting the concrete blocks from which they were cored. Expansion measurements were taken every 7 days for the first 28 days of conditioning and then monthly up to 1 year.

The sealed cores were to represent concrete in the internal part of a structure that is exposed to the least amount of water, and ASR is driven only by the alkali hydroxides in the pore solution.

The modified ASTM C1260 conditioning involved immersing cores in 1 N NaOH at various temperatures to accelerate ASR and represented the most severe exposure conditions.

The modified ASTM C1293 conditioning was representative of concrete supplied by moisture in the air.

4.2.2 Late-age conditioning and testing

Late-age testing was performed on three cores from each mixture approximately 4 months after remaining in ambient laboratory conditions to investigate the effect of aging prior to exposure to 1 N NaOH at 80 °C. This modified ASTM C1260 exposure condition was selected based on the results of the early-age conditioning conditions that identified the 1 N NaOH high-temperature exposure to be the most viable for producing measureable expansion. Table 44 provides a summary of the residual expansion tests conducted in this study.

Table 4. Summary of residual expansion testing for M1R and M2R cores.

Mixture ID	Pre-conditioning designator	Pre-conditioning of specimens before testing	Age of specimens at conditioning (days)	Conditioning	Conditioning temperature
M1R	Early age	Stored in ambient lab temperature environment	28	Sealed	23, 38, 60, 80 °C
				Immersed in 1 N NaOH (modified ASTM C1260)	23, 38, 60, 80 °C
				Over Water (modified ASTM C1293)	23, 38, 60, 80 °C
	Late age	Immersed in tap water at 23 +/- 2 °C for 35 days	117	Immersed in 1 N NaOH (modified ASTM C1260)	80 °C
M2R	Early age	Stored in ambient lab temperature environment	28	Sealed	23, 38, 60, 80 °C
				Immersed in 1 N NaOH (modified ASTM C1260)	23, 38, 60, 80 °C
				Over water (modified ASTM C1293)	23, 38, 60, 80 °C
	Late age	Immersed in tap water at 23 +/- 2 °C for 35 days before testing	117	Immersed in 1 N NaOH (modified ASTM C1260)	80 °C

4.3 Mechanical properties

To determine the mechanical properties of ASR-damaged concrete, 3- x 6-in. cylinders were cast and subjected to similar conditioning regimes as the M1M and M2M residual expansion cores. Test methods for evaluating the concrete mechanical properties were as follows: (1) compressive strength in accordance with ASTM C39, (2) splitting tensile strength in accordance with ASTM C496, and (3) static modulus of elasticity in accordance with ASTM C469. An Instron 600DX loading frame was used for all tests. Conditioning of the cylinders for testing concrete mechanical properties is divided into two phases, i.e., immediate conditioning and delayed conditioning.

4.3.1 Immediate conditioning

In immediate conditioning, the cylinders were stored in a moist curing room at 23 °C and 100 percent RH for 24 hr prior to demolding. The cylinders were then immersed in 1 N NaOH and brought up to 80 °C, where they remained until they were tested. Tests were conducted after 4, 7, 28, and 56 days of conditioning.

4.3.2 Delayed conditioning

It was concluded that the progression of ASR and the initial strength gain of the concrete were in competition in the immediate conditioning regime. Therefore, delayed conditioning, using only aggregate M2, was later established to investigate the effect of curing duration on the reduction in mechanical properties due to ASR deterioration. The M1 aggregate was not used in the delayed conditioning phase due to unexpected low residual expansion results.

An additional set of cylinders was cast and cured for 90 days in a moist room at 23 ºC and 100 percent RH to permit the concrete to reach a relatively steady state prior to conditioning in the 1 N NaOH solution at 80 ºC until testing. Control cylinders were also cast and stored at 23 ºC and 100 percent RH without exposure to 1 N NaOH during this phase. Table 5 provides a summary of the mechanical properties conditioning and testing.

Table 5. Summary of conditioning of M1M and M2M cylinders for measuring mechanical properties.

Mixture ID	Total number of specimens	Conditioning designator	Curing and conditioning	Test temperature (°C)	Test methods	Concrete test age (days)
Immediate conditioning						
M1M	36	Immediate conditioning	Cured 24 hr then submerged in 1 N NaOH	80	Compressive strength	4, 7, 28, 56
					Splitting tensile	
					Modulus of elasticity	
M2M	36	Immediate conditioning	Cured 24 hr then submerged in 1 N NaOH	80	Compressive strength	4, 7, 28, 56
					Splitting tensile	
					Modulus of elasticity	
Delayed conditioning						
M2M	90	Control	Cured at 100% RH until testing age	23	Compressive strength	1, 4, 7, 28, 56, 91, 95, 98, 119, 147
					Splitting tensile	
					Modulus of elasticity	
	45	Delayed conditioning	Cured 90 days at 100% RH then submerged in 1 N NaOH	80	Compressive strength	91, 95, 98, 119, 147
					Splitting tensile	
					Modulus of elasticity	

5 Results and Discussion

5.1 Standardized test methods

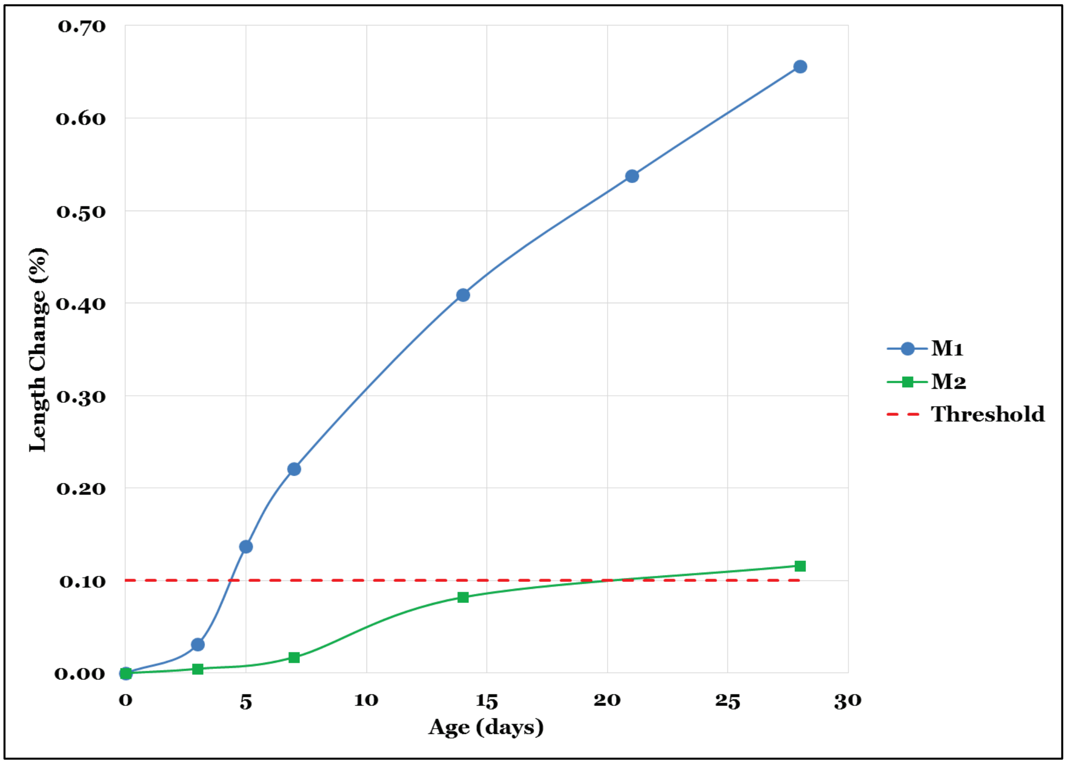
5.1.1 ASTM C1260 accelerated mortar bar test

The results of ASTM C1260 are provided in Table 6 and Figure 4. The M1S mortar bars expanded nearly 4.7 times more than the M2S mortar bars at 28 days. At day 7, the M1S aggregate surpassed the 0.2 percent expansion limit presented in the standard. The M2S aggregate appeared to be innocuous at 14 days, but expansion at 28 days fell between the 0.1 and 0.2 percent limits in the standard, meaning that further testing should be conducted on the aggregate in order to draw conclusions about its reactivity.

Table 6. Summary of results from the ASTM C1260 AMBT.

Specimen age (days)	Average length change (%)	
	M1S	M2S
3	0.031	0.005
7	0.221	0.017
14	0.410	0.082
28	0.656	0.116

Figure 4. Average length change of M1S and M2S mortar bars in ASTM C1260.



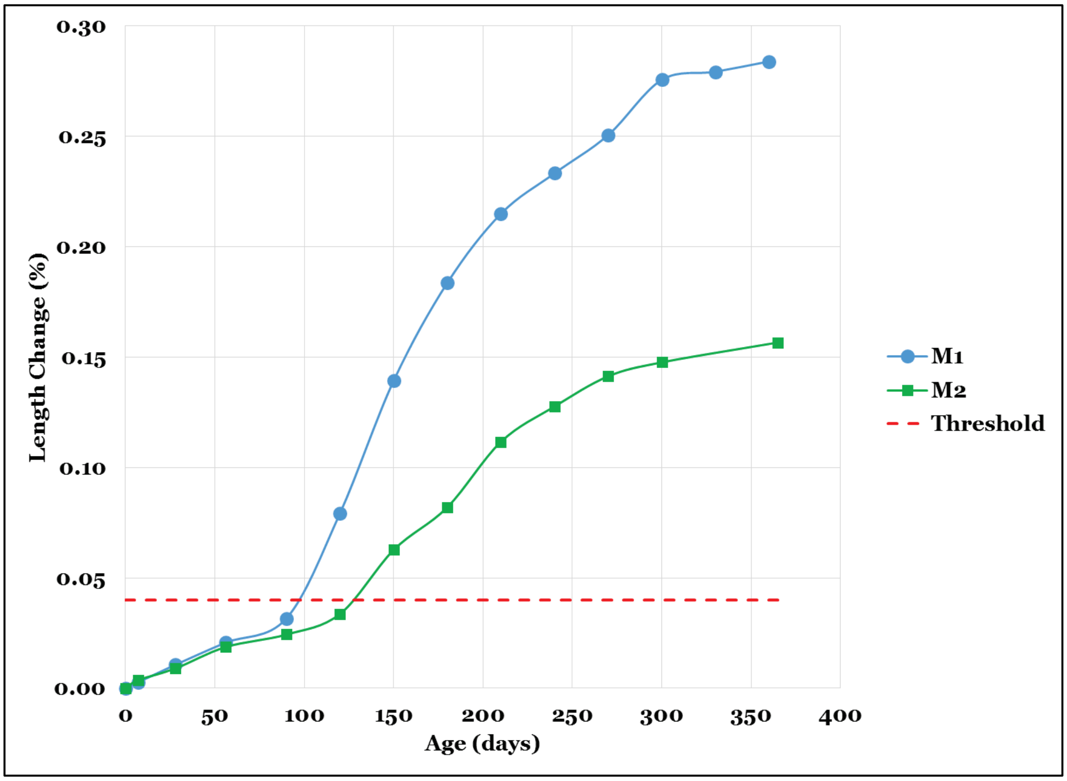
5.1.2 ASTM C1293 concrete prism test

The results of ASTM C1293 are summarized in Table 7 and illustrated in Figure 5. Each data point represents the average expansion of three concrete prisms. The M1S prisms showed greater expansion than the M2S prisms. The final ASTM C1293 expansions exhibited by M1S and M2S were 0.284 percent and 0.157 percent, respectively. Both aggregates were considered reactive based on an expansion limit of 0.04 percent suggested in ASTM C1293.

Table 7. Summary of average length change of M1S and M2S prisms in ASTM C1293.

Specimen age (days)	Average length change (%)	
	M1S	M2S
28	0.011	0.009
56	0.021	0.019
90	0.032	0.024
180	0.184	0.082
270	0.251	0.141
365	0.284	0.157

Figure 5. Average length change of M1S and M2S prisms in ASTM C1293.



5.2 Residual expansion

5.2.1 Sealed cores

The average length changes of sealed M1R and M2R cores are shown in Figure 6. and 7, respectively.

Figure 6. Average length change of sealed M1R cores.

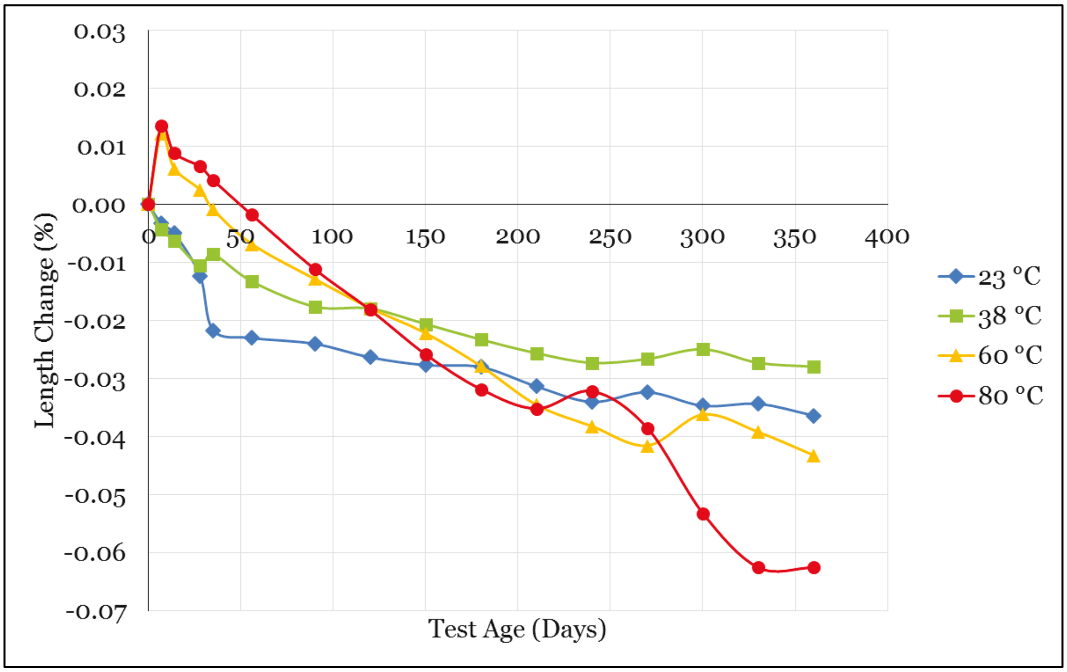
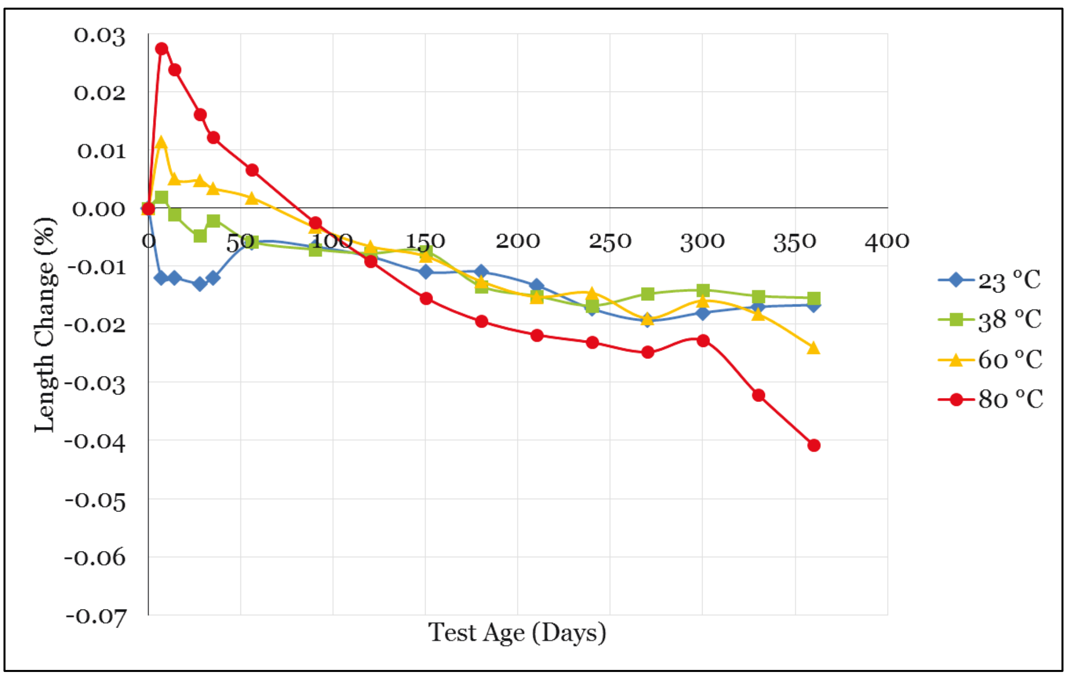


Figure 7. Average length change of sealed M2R cores.



All sealed cores experienced shrinkage rather than expansion over time. Initially, M1R and M2R cores at 60 and 80 °C expanded, but they began to exhibit shrinkage by the 14-day reading. At 360 days of conditioning, cores conditioned at 80 °C demonstrated the most shrinkage compared to cores conditioned at lower temperatures. This shrinkage was possibly caused by moisture intake of ASR product, which led to drying of the cores and internal self-desiccation. Boosting the mixing water with alkalis may have permitted expansion of the sealed cores. The results indicate that self desiccation is an important driver for ASR-induced expansion, since it was clearly suppressed, and the total length change was dominated by shrinkage. This condition was identified to not be a viable candidate to consider for future residual expansion capacity testing for in-situ concrete from existing structures.

5.2.2 Modified ASTM C1260

Expansions of M1R and M2R cores subjected to modified ASTM C1260 conditions are presented in Figure 8 andFigure 9, respectively. A gap in the data for the M1R cores at 80 °C exists due to evaporation of the solution and subsequent drying of the cores caused by faulty container lids. After the drying had been detected, the containers were replenished with 1 N NaOH solution, and readings continued to be taken on those cores.

Figure 8. Expansion of M1R cores in modified ASTM C1260 conditions.

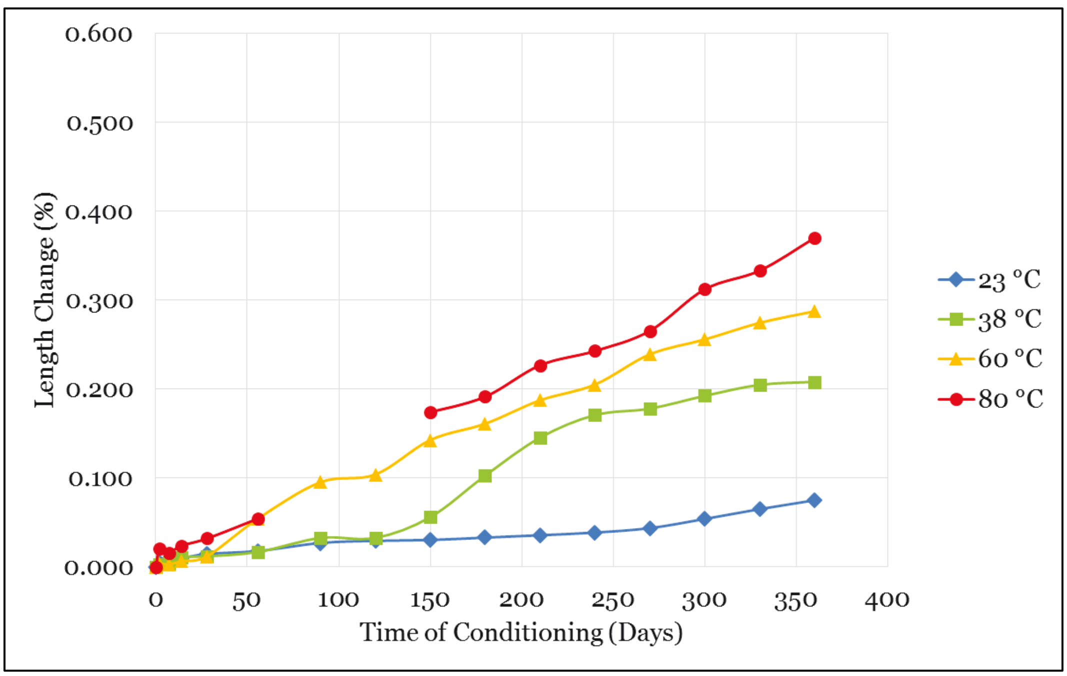
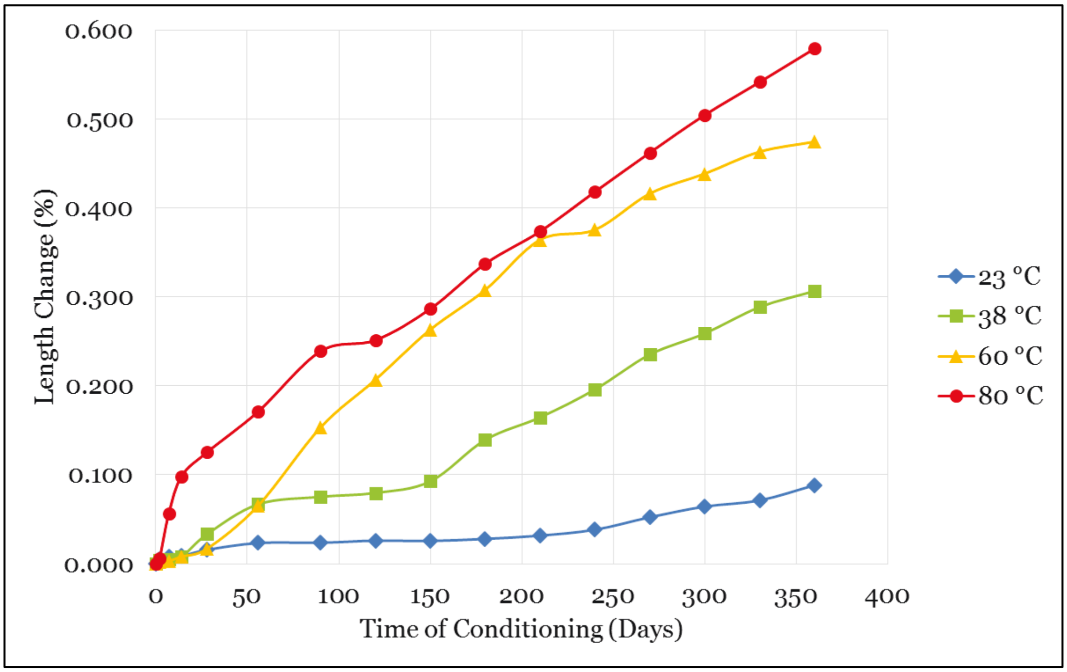


Figure 9. Expansion of M2R cores in modified ASTM C1260 conditions.



The expansions of the cores increased as the conditioning temperatures increased in modified ASTM C1260 conditions. M2R cores exhibited higher expansions than M1R cores at all temperatures. Because both the specimen type and size used in this study differed significantly from those of specimens used in the standardized test method, the expansion limit specified in the standard does not apply here. However, expansions are considered to be significant for both mixtures in this conditioning regime.

5.2.3 Modified ASTM C1293

The expansions of M1R and M2 drilled cores in modified ASTM C1293 conditions are provided in Figure 10 and 11, respectively. Length change measurements on cores conditioned at 60 and 80 °C concluded at 120 days of conditioning rather than at 360 days due the inability to maintain 100 percent RH at the high temperatures from rapid loss of moisture from the containers. Nonetheless, these high temperature tests did result in an acceleration of expansion.

Figure 10. Expansion of M1R cores in modified ASTM C1293 conditions.

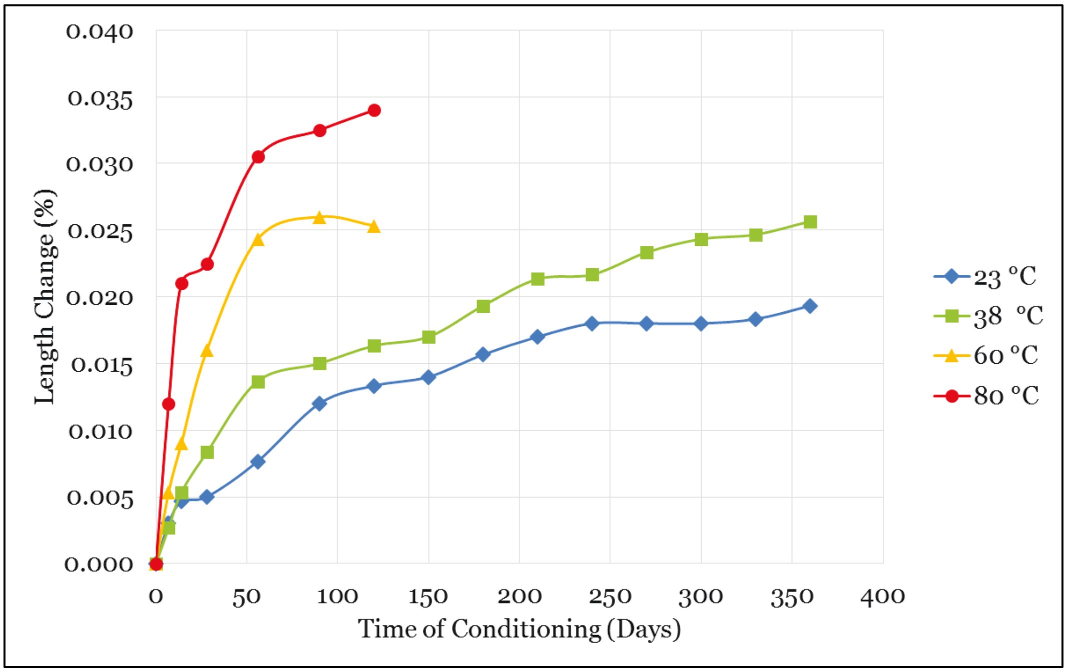
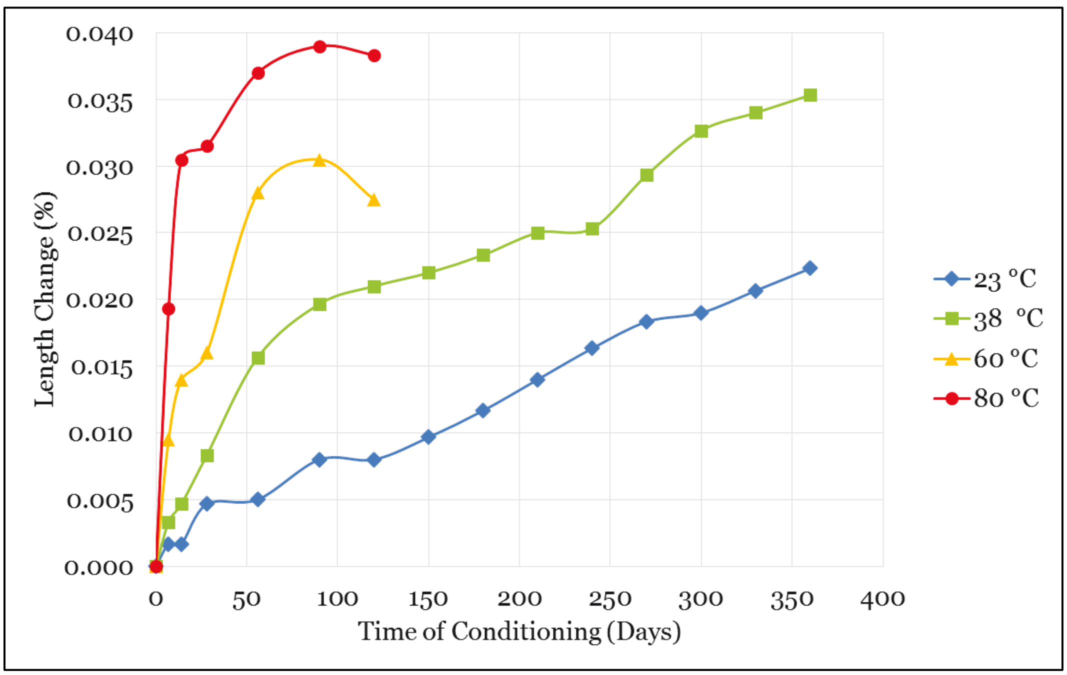


Figure 11. Expansion of M2R cores in modified ASTM C1293 conditions.



At higher conditioning temperatures, the cores experienced increasingly higher expansions. At all temperatures, M2R cores expanded more than M1R cores. Aggregate M1R is known to be highly reactive and has been used in previous laboratory ASR studies as a reactive benchmark aggregate. In this study, the relatively low expansions achieved by specimens containing the aggregate in all M1 tests were unexpected. As a result, petrographic analysis was performed on the aggregate, and it was determined that the mineralogy was different from past analyses.

Neither M1R nor M2R cores expanded enough to reach the 0.04 percent expansion limit of ASTM C1293, even at elevated temperatures (60 and 80 °C) at 120 days. This is almost certainly due to the lack of alkali boosting in the mixtures. The standard and accelerated ASTM C1293 have been shown to induce alkali leaching from the concrete prisms (Ideker et al. 2010). Alkali leaching in this study likely resulted in a shortage of alkali hydroxides available to participate in ASR.

5.2.4 Effect of late-age conditioning in modified ASTM C1260

The impact of the late-age conditioning on concrete core expansion is summarized in Table 8 and illustrated in Figure 12.

An approximate 3 percent loss in expansion resulted from the late-age conditioning for both M1R and M2R cores at 1 year. This is possibly due to alkali leaching when the cores were submerged in water 35 days prior to testing. Another possible explanation is that early-age expansion, which occurred during the initial 4-month curing period, was not captured in the data because measuring began later. Regardless of the cause, the impact of the conditioning time was negligible in regards to the final age expansion for both mixtures.

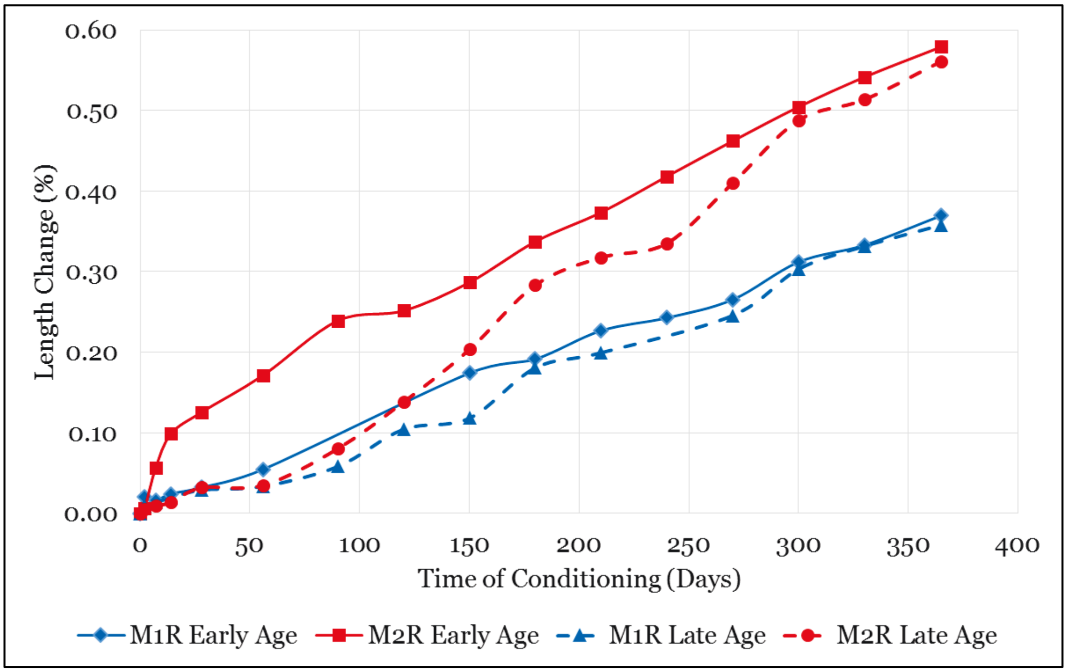
Table 8. Comparison of early- and late-age conditioning of cores in modified C1260 conditions.

Mixture ID	[1]Early-age expansion	[2]Late-age expansion	% Difference
M1R	0.370%	0.358%	3.2%
M2R	0.579%	0.561%	3.1%

[1] Conditioning of specimens began 28 days after coring from concrete block.

[2] Conditioning of specimens began approximately 4 months after coring from concrete block.

Figure 12. Comparison of core expansions at early- and late-age testing.



5.3 Mechanical properties

5.3.1 Immediate conditioning

The results of compressive strength, splitting tensile strength, and modulus of elasticity of M1M and M2M cylinders stored in 1 N NaOH at 80 °C up to 56 days are summarized in Table 9 and shown in Figures 13-15. Overall, the M2M cylinders resulted in higher strengths and modulus of elasticity compared to the M1M cylinders. No reductions in the strength over time were observed due to the continued hydration of the cement and/or due to the expansive gel filling any cracks due to the ASR formation.

Table 9. Results obtained for mechanical property tests after immediate exposure to 1 N NaOH at 80 °C.

Days of exposure to 1 N NaOH at 80 °C	Compressive strength (psi)		Splitting tensile strength (psi)		Modulus of elasticity (ksi)	
	M1M	M2M	M1M	M2M	M1M	M2M
4	3310	3880	430	380	2.56	2.73
7	3660	3880	460	420	3.15	3.02
28	3730	4420	595	670	3.47	3.67
56	4400	5197	595	686	3.75	4.23

Figure 13. Compressive strength of M1M and M2M cylinders exposed to 1 N NaOH at 80 °C.

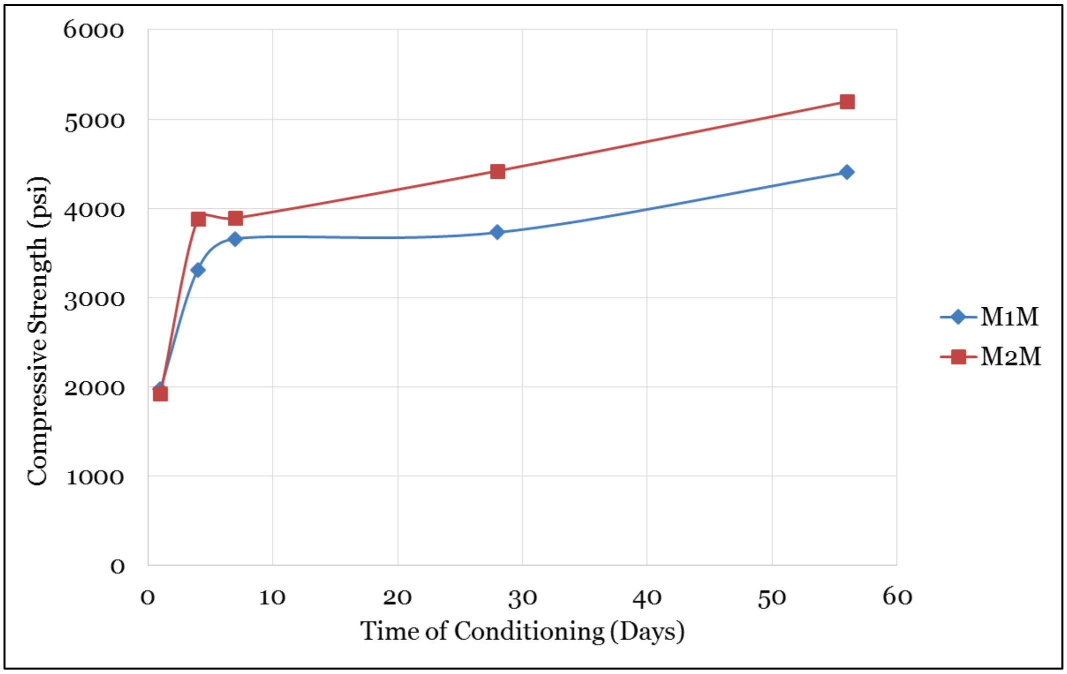


Figure 14. Splitting tensile strength of M1M and M2M cylinders exposed to 1 N NaOH at 80 °C.

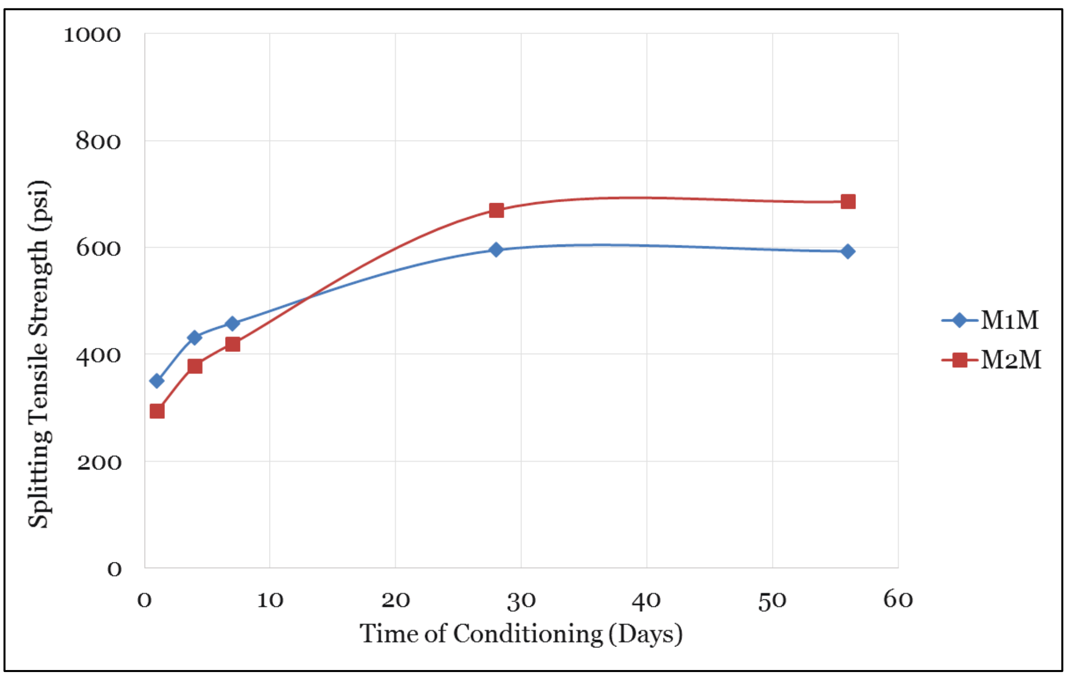
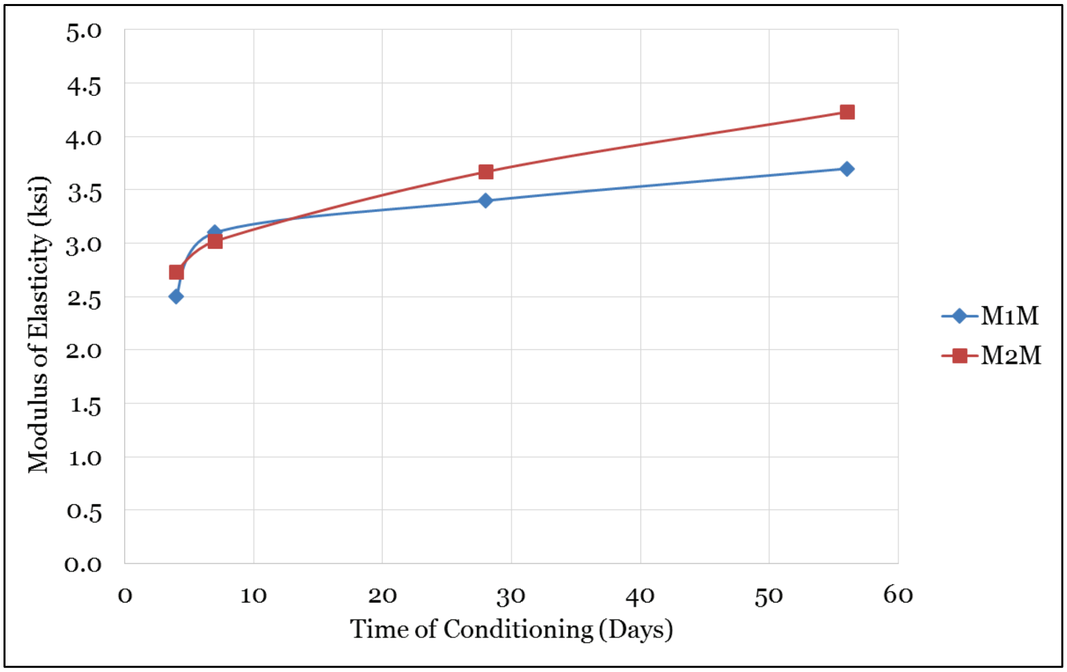


Figure 15. Modulus of elasticity of M1M and M2M cylinders exposed to 1 N NaOH at 80 °C.



5.3.2 Delayed conditioning

The effect of ASR on the mechanical properties of the M2M cylinders was investigated after delayed conditioning. Compressive strength, splitting tensile strength, and modulus of elasticity for each conditioning regime of M2M cylinders are shown in Figure 16-18. In this case, a control series was also tested to serve as a baseline for comparison to aid in identification of strength degradation.

Figure 16. Compressive strengths of M2M control, immediate-conditioning, and delayed-conditioning cylinders.

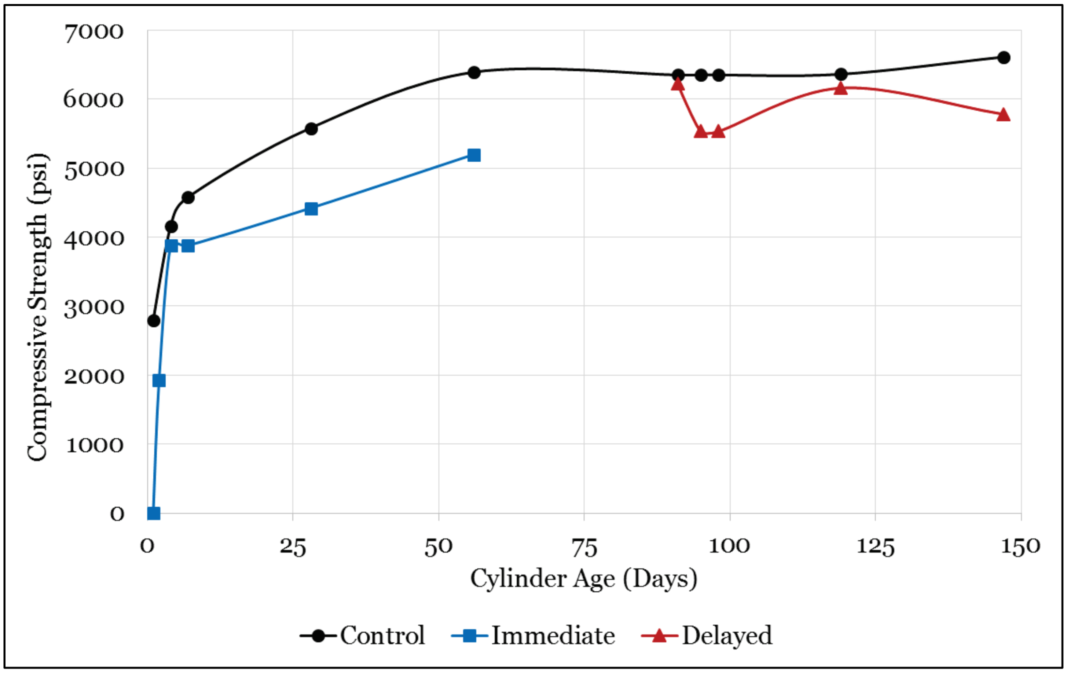


Figure 17. Splitting tensile strengths of M2M control, immediate-conditioning, and delayed-conditioning cylinders.

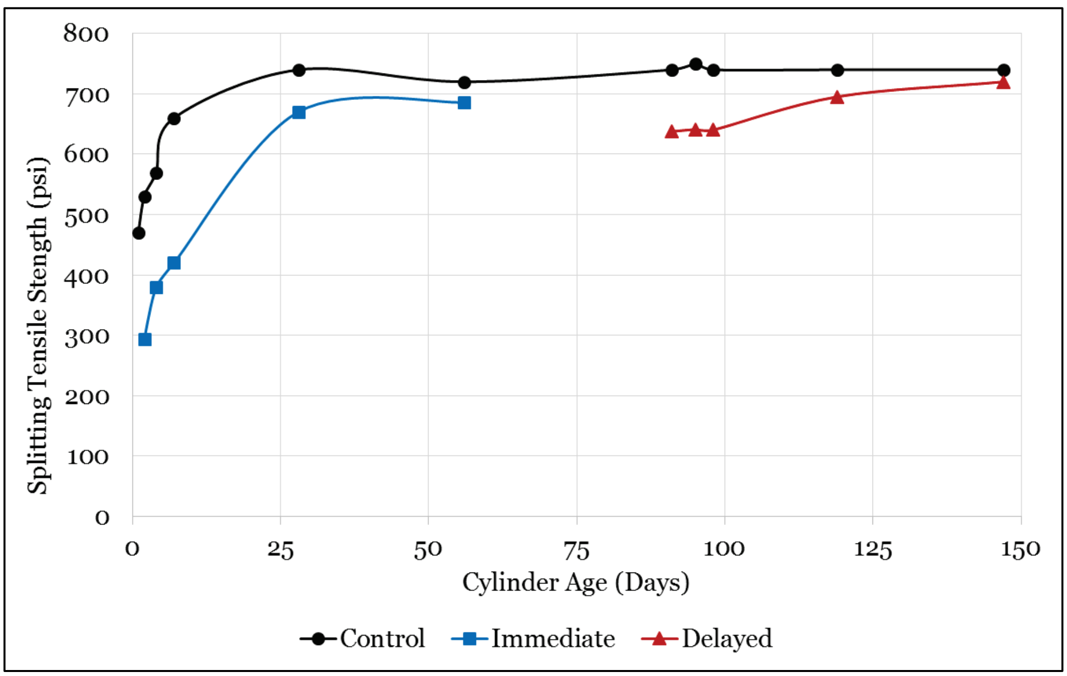
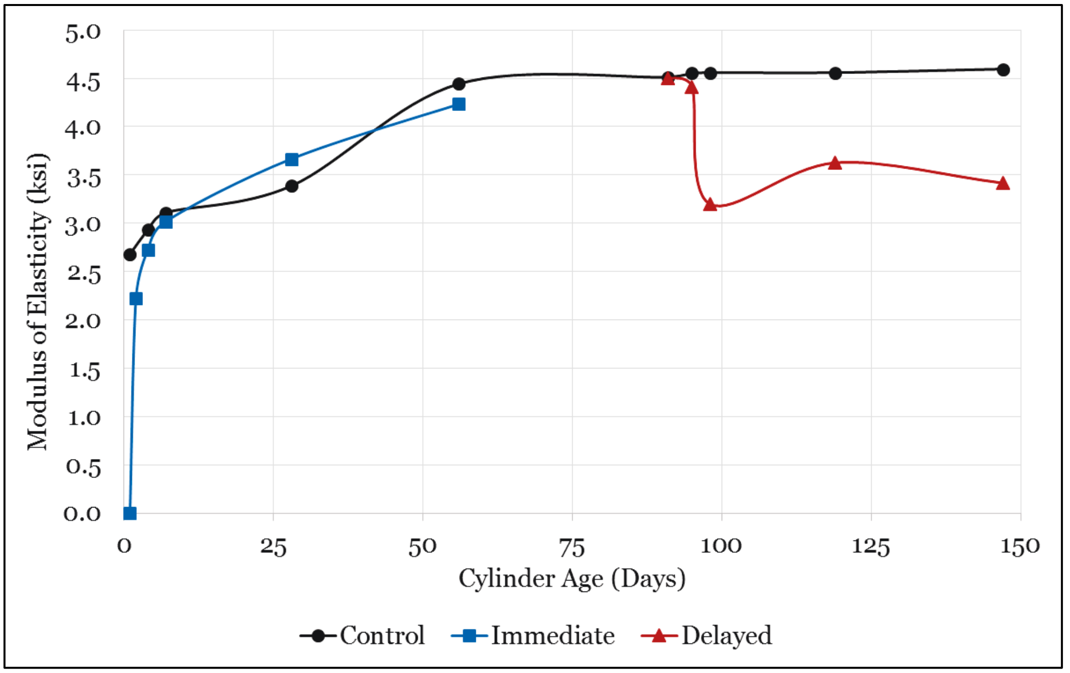


Figure 18. Moduli of elasticity of M2M control, immediate-conditioning, and delayed-conditioning cylinders.



The reductions in the mechanical properties for immediate and delayed conditioning in comparison with the control cylinders are summarized Table 10. In the table, the control cylinders are indicated by "A," and the conditioned cylinders are indicated by "B." All results are the average of three cylinders.

The control cylinders performed as expected over time. Results of cylinders immediately conditioned in 1 N NaOH for compressive strength, splitting tensile strength, and modulus of elasticity showed average reductions of 18, 17, and 3 percent, respectively, compared to the control cylinders. Delayed conditioning in 1 N NaOH resulted in average compressive strength, splitting tensile strength, and modulus of elasticity reductions of 10, 7, and 25 percent, respectively, compared to the control cylinders.

Table 10. Results of mechanical properties of M2M cylinders for immediate and delayed conditioning.

Days of conditioning	[1]Immediate Conditioning								
	Compressive strength (psi)			Splitting tensile strength (psi)			Modulus of elasticity (ksi)		
	A	B	% Reduction	A	B	% Reduction	A	B	% Reduction
7	4580	3880	15	660	420	36	3.11	3.02	3
28	5580	4420	21	740	670	9	3.75	3.67	2
56	6390	5197	19	720	686	5	4.44	4.23	5
	Average:		18			17			3
Days of conditioning	[2]Delayed conditioning								
	Compressive strength (psi)			Splitting tensile strength (psi)			Modulus of elasticity (ksi)		
	A	B	% Reduction	A	B	% Reduction	A	B	% Reduction
7	6350	5530	13	740	640	13	4.56	3.20	30
28	6360	6160	3	740	695	6	4.56	3.63	20
56	6610	5780	13	740	720	3	4.60	3.42	26
	Average:		10			7			25

[1] Conditioned cylinders were immersed in 1 N NaOH at 80 °C after curing for 24 hr.

[2] Conditioned cylinders were immersed in 1 N NaOH at 80 °C after curing for 90 days at 100% RH.

A – Control cylinders

B – Conditioned cylinders

The immediate- and delayed-conditioning compressive strength reductions were in agreement with Ahmed et al. (2003) who reported an average 12.7 percent reduction compared to control specimens at 1 year for 4- x 4- x 4-in. cubes. Conditioning in that study involved immersing the specimens in water at 38 °C. Marzouk and Langdon (2003) reported an average reduction of 24 percent at 12 weeks for 3- x 6-in. cylinders in NaOH at 80 °C. Both the immediate- and delayed-conditioning reductions in compressive strength in this study were lower than 24 percent, but conditioning was ended 28 days sooner than was done in the study by Marzouk and Langdon. Giaccio et al. (2008) conditioned 4- x 8-in. cylinders in water at 38 °C and reported reductions of 28, 63, and 2.5 percent at 75, 250, and 745 days, respectively. Each of those reductions was based on a different mixture and used a different reactive aggregate or aggregate combination than the other two mixtures.

Reductions in splitting tensile strength and modulus of elasticity were much lower than those reported by Ahmed et al. (2003); they observed average reductions of 35.6 and 65.2 percent for splitting tensile strength (4- x 4-in. cylinders) and modulus of elasticity (6- x 12-in. cylinders), respectively, at 1 year in water at 38 °C. Multon et al. (2005) reported 15 and 37 percent reductions in splitting tensile strength (4- x 8-in. cylinders) and modulus of elasticity (6- x 12-in. cylinders), respectively, for boosted specimens sealed in aluminum for 1 year. Giaccio et al. (2008) observed 52, 189, and 24 percent reductions in modulus of elasticity for 4- x 8-in. cylinders at 75, 250, and 745 days, respectively; those cylinders were from different mixtures, as previously described.

In this study, delaying the conditioning had the most significant effect on the modulus of elasticity, which is the mechanical property reported in the literature to be the most sensitive to ASR deterioration. For immediate conditioning, the cylinders continued to gain in both strengths and modulus of elasticity during the 56-day conditioning period. For delayed conditioning, however, reductions in the mechanical properties were observed to take place between the 28-day and 56-day readings. Studies in the literature typically carried out measurements up to 1 year and showed relatively high reductions in these properties. Had conditioning and measurements continued beyond 56 days in this study, an increase in reductions of the mechanical properties would likely have been observed.

6 Conclusions and Recommendations

The following conclusions and recommendations for future research can be made based on the results of this study.

- Expansions for M1S were higher than expansions for M2S in both ASTM C1260 and ASTM C1293. However, the experimental residual expansions tests modifying the ASTM C1260 and C1293 on core samples resulted in lower expansions of the M1R coarse aggregate than anticipated. It is unclear why the M1R showed less expansion than the M2R in the residual expansion test methods. This will be a subject of further investigation.
- Expansions increased as conditioning temperatures increased in all modified test methods for residual expansion.
- If no external alkalis are to be supplied by immersing laboratory specimens in solution, then the mixing water must be boosted to provide enough alkalis to promote ASR in conditions where alkali leaching occurs. The unboosted M1R and M2R cores in this study did not achieve significant expansions in the sealed and modified ASTM C1293 conditions despite the use of elevated temperatures.
- Not measuring the expansion of the residual expansion cores during for 4 months after coring may have led to a lower result for the overall ASR expansion. However, only a 3 percent reduction in expansion was observed between the early- and late-age conditioning regimes at 1 year. Therefore, if overall expansion after a long period of time, e.g., 1 year, is of primary interest, then a substantial interval between casting and conditioning specimens is unnecessary.
- Delayed conditioning of the cylinders used for measuring mechanical properties affected the modulus of elasticity more than it affected the compressive and splitting tensile strengths. Only a 3 percent reduction in the modulus of elasticity was observed in cylinders immediately conditioned compared to a 25 percent reduction in the modulus of elasticity for cylinders conditioned after 90 days of curing. In the case of immediate conditioning, it appears that the inherent strength gain over time counteracted the reduction in mechanical properties up to 56 days.
- Studies on the mechanical properties of ASR-affected concretes in the literature typically involved conditioning and measurements up to 1 year and showed significant reductions in those properties. In most cases, these reductions did not occur until at or beyond 75 days of

conditioning. It is recommended that studies be conducted for longer than 56 days to properly capture decreases in compressive strength, splitting tensile strength, and modulus of elasticity.

References

Ahmed, T., E. Burley, S. Rigden, and A.I. Abu-Tair. 2003. The effect of alkali reactivity on the mechanical properties of concrete. *Construction and Building Materials* 17:123-144.

Bérubé, M.A., J. Duchesne, J.F. Dorion, and M. Rivest. 2002. Laboratory assessment of alkali contribution by aggregates to concrete and application to concrete structures affected by alkali-silica reactivity. *Cement and Concrete Research* 32 (8):1215-1227.

Giaccio, G., R. Zerbino, J.M. Ponce, and O.R. Batic. 2008. Mechanical behavior of concretes damaged by alkali-silica reaction. *Cement and Concrete Research* 38:993-1004.

Ideker, J., B. East, K.J. Folliard, M.D.A. Thomas, and B. Fournier. 2010. The current state of the accelerated concrete prism test. *Cement and Concrete Research* 40 (4):550-555.

Leemann, A., and C. Merz. 2013. An attempt to validate the ultra-accelerated microbar and the concrete performance test with the degree of AAR-induced damage observed in concrete structures. *Cement and Concrete Research* 49:29-37.

Lu, D., B. Fournier, P.E. Grattan-Bellew, Z. Xu, and M. Tang. 2008. Development of a universal accelerated test for alkali-silica and alkali-carbonate reactivity of concrete aggregates. *Materials and Structures* 41 (2):235-246.

Marzouk, H., and S. Langdon. 2003. The effect of alkali-aggregate reactivity on the mechanical properties of high and normal strength concrete. *Cement and Concrete Composites* 25:549-556.

Merz, C., and A. Leemann. 2013. Assessment of the residual expansion potential of concrete from structures damaged by AAR. *Cement and Concrete Research* 52:182-189.

Multon, S., J. F. Seignol, and F. Toutlemonde. 2005. Structural behavior of concrete beams affected by alkali-silica reaction. *ACI Materials Journal* 102 (2):67-76.

Multon, S., F.X. Barin, B. Godart, and F. Toutlemonde. 2008. Estimation of the residual expansion of concrete affected by alkali silica reaction. *Journal of Materials in Civil Engineering* 20 (1):54-62.

Appendix A: Material Reports

Holcim Type I/II Cement

Holcim

Material Certification Report

Material:	Portland Cement	Test Period:	01-Apr-2016
Type:	I-II	To:	30-Apr-2016

Certification

This Holcim cement meets the specifications of ASTM C150 for Type I-II cement, and complies with AASHTO M85 specifications for Type I-II cement.

General Information

Supplier:	Holcim (US) Inc.	Source Location:	Ste. Genevieve Plant
Address:	2942 US Highway 61 Bloomsdale, MO 63627		2942 US Highway 61 Bloomsdale, MO 63627
Telephone:	636-524-8155	Contact:	Erin Watson
Date Issued:	13-May-2016		

The following information is based on average test data during the test period.
The data is typical of cement shipped by Holcim; individual shipments may vary.

Tests Data on ASTM Standard Requirements

Chemical

Item	Limit[A]	Result
SiO_2 (%)	-	19.7
Al_2O_3 (%)	6.0 max	4.4
Fe_2O_3 (%)	6.0 max	3.2
CaO (%)	-	64.5
MgO (%)	6.0 max	2.3
SO_3 (%)	3.0 max[B]	3.5
Loss on Ignition (%)	3.5 max[E]	2.6
Insoluble Residue (%)	1.5 max	0.54
CO_2 (%)	-	1.4
Limestone (%)	5.0 max	3.6
$CaCO_3$ in Limestone (%)	70 min	89
Inorganic Processing Addition (%)	5.0 max	0.4
Potential Phase Compositions[C]:		
C_3S (%)	-	65
C_2S (%)	-	6
C_3A (%)	8 max	6
C_4AF (%)	-	10
$C_3S + 4.75C_3A$ (%)	-	94.4

Physical

Item	Limit[A]	Result
Air Content (%)	12 max	6
Blaine Fineness (m^2/kg)	260 min	394
Autoclave Expansion (%) (C151)	0.80 max	0.04
Compressive Strength MPa (psi):		
3 days	12.0 (1740) min	28.9 (4200)
7 days	19.0 (2760) min	36.4 (5270)
Initial Vicat (minutes)	45-375	90
Mortar Bar Expansion (%) (C1038)	-	0.014

Tests Data on ASTM Optional Requirements

Chemical

Item	Limit[A]	Result
Equivalent Alkalies (%)	0.60 max	0.54

Physical

Item	Limit[A]	Result
False Set (%)	50 min	85

Notes

[A] Dashes in the limit / result columns mean Not Applicable.
[B] It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020 % at 14 days.
[C] Adjusted per Annex A1.6 of ASTM C150 and AASHTO M85.
[D] Test result represents most recent value and is provided for information only. Analysis of Heat of Hydration has been carried out by CTLGroup, Skokie, IL.
[E] Limit = 3.0 when limestone is not an ingredient in the final cement product
Equivalent Alkalies (%) Minimum = 0.5, Maximum = 0.58
This data may have been reported on previous mill certificates.

Additional Data

Inorganic Processing Addition Data

Item	Result[A]
Type	IPA
Amount (%)	0.4
SiO_2 (%)	10.4
Al_2O_3 (%)	3.2
Fe_2O_3 (%)	1.6
CaO (%)	65.2
SO_3 (%)	0.6

Base Cement Phase Composition

Item	Result
C_3S (%)	68
C_2S (%)	6
C_3A (%)	6
C_4AF (%)	10

Green Brothers Concrete Sand

Worksheet			FINE AGGREGATE	Green Bros. Sand OCT-12_mar edits.xlsx	
Serial No.:	120087	TPP:		Date:	Sep-12 Tested By: CEERD-GM-C
WIC:		District:	CMB	Contract No.:	Lab Stock
Producer:	Green Bros			Date Recd:	Oct-12
Sampled By:	B. Green			Matl Type:	Natural Sand

ASTM C 136 Sieve Analysis:

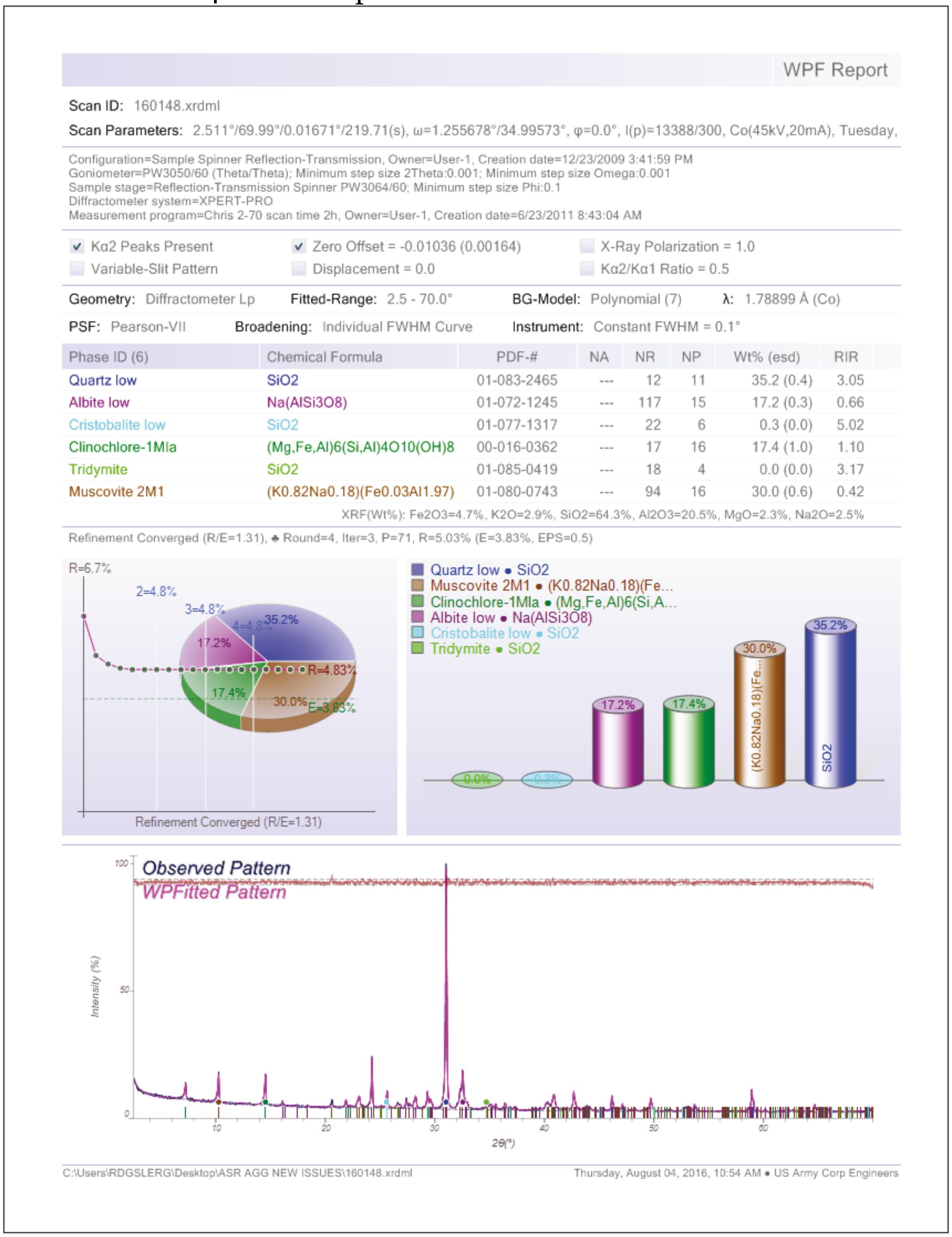
	Run 1		Cumulative Percent		
Sieve Size	Mass Ret, g	% Ret.	Ret.	Pass	Avg
3/8 in.	0.00	0.00%	0.00%	100.00%	100%
No. 4	3.80	0.84%	0.84%	99.16%	99%
No. 8	33.06	7.30%	8.14%	91.86%	92%
No. 16	38.05	8.40%	16.54%	83.46%	83%
No. 30	90.75	20.03%	36.57%	63.43%	63%
No. 50	243.74	53.81%	90.38%	9.62%	10%
No. 100	41.92	9.25%	99.63%	0.37%	0%
No. 200	1.36	0.30%	99.93%	0.07%	0%
Pan	0.31	0.07%	100.00%		
Total	452.99	100.00%			
Fineness Modulus:			2.521		2.52

ASTM C 128 Bulk Specific Gravity & Absorption:

Flask No.	3	Avg
SSD Mass, g	500.50	
Mass Flask+Water, g	679.40	
Mass Flask+Water+Material, g	989.70	
Mass Displaced Water, g	190.20	
Water Temp C	22.5	
Relative Density (Bulk Specific Gravity)(SSD)	2.631	2.63
SSD Mass, g	500.80	
Oven Dry Mass, g	499.00	
Moisture Loss, g	1.80	
Absorption	0.36%	0.4%

Appendix B: XRD Summary Reports

CA1: CMB 160148 WPF Report



WPF Report

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Sample stage=Reflection-Transmission Spinner PW3064/60; Minimum step size Phi:0.1
Diffractometer system=XPERT-PRO
Measurement program=Chris 2-70 scan time 2h, Owner=User-1, Creation date=6/23/2011 8:43:04 AM

☑ Kα2 Peaks Present ☑ Zero Offset = -0.01036 (0.00164) ☐ X-Ray Polarization = 1.0
☐ Variable-Slit Pattern ☐ Displacement = 0.0 ☐ Kα2/Kα1 Ratio = 0.5

Geometry: Diffractometer Lp **Fitted-Range:** 2.5 - 70.0° **BG-Model:** Polynomial (7) **λ:** 1.78899 Å (Co)

PSF: Pearson-VII **Broadening:** Individual FWHM Curve **Instrument:** Constant FWHM = 0.1°

Phase ID (6)	Chemical Formula	PDF-#	NA	NR	NP	Wt% (esd)	RIR
Quartz low	SiO2	01-083-2465	---	12	11	35.2 (0.4)	3.05
Albite low	Na(AlSi3O8)	01-072-1245	---	117	15	17.2 (0.3)	0.66
Cristobalite low	SiO2	01-077-1317	---	22	6	0.3 (0.0)	5.02
Clinochlore-1Mla	(Mg,Fe,Al)6(Si,Al)4O10(OH)8	00-016-0362	---	17	16	17.4 (1.0)	1.10
Tridymite	SiO2	01-085-0419	---	18	4	0.0 (0.0)	3.17
Muscovite 2M1	(K0.82Na0.18)(Fe0.03Al1.97)	01-080-0743	---	94	16	30.0 (0.6)	0.42

XRF(Wt%): Fe2O3=4.7%, K2O=2.9%, SiO2=64.3%, Al2O3=20.5%, MgO=2.3%, Na2O=2.5%

Refinement Converged (R/E=1.31), ♣ Round=4, Iter=3, P=71, R=5.03% (E=3.83%, EPS=0.5)

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CA2 CMB 160136 WPF Report

WPF Report

Scan ID: 160136.xrdml

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Diffractometer system=XPERT-PRO
Measurement program=Chris 2-70 scan time 2h, Owner=User-1, Creation date=6/23/2011 8:43:04 AM

✔ Kα2 Peaks Present	✔ Zero Offset = 0.00391 (0.0014)	X-Ray Polarization = 1.0
Variable-Slit Pattern	Displacement = 0.0	Kα2/Kα1 Ratio = 0.5

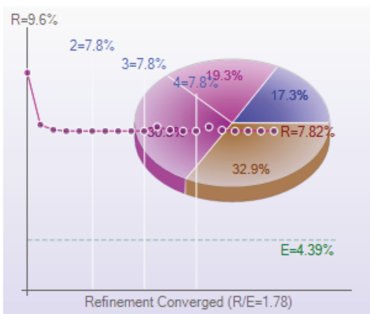
Geometry: Diffractometer Lp **Fitted-Range:** 3.5 - 70.0° **BG-Model:** Polynomial (6) **λ:** 1.78899 Å (Co)

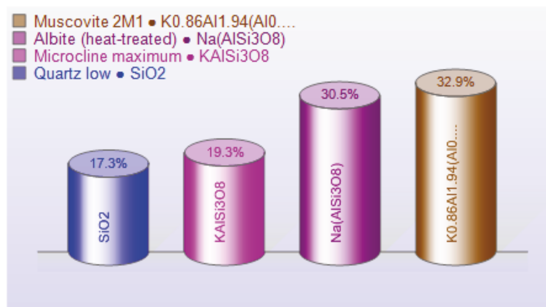
PSF: Pearson-VII **Broadening:** Individual FWHM Curve **Instrument:** Constant FWHM = 0.1°

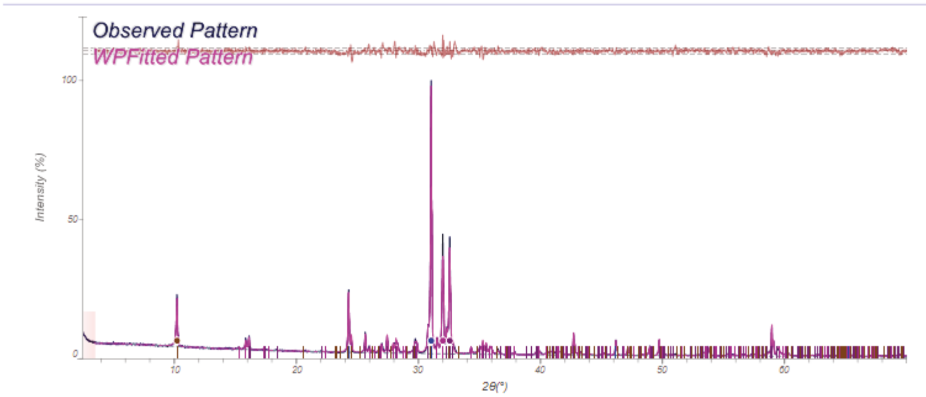
Phase ID (4)	Chemical Formula	PDF-#	NA	NR	NP	Wt% (esd)	RIR
Quartz low	SiO2	01-083-2465	---	12	11	17.3 (0.2)	3.05
Microcline maximum	KAlSi3O8	01-072-1114	---	115	15	19.3 (0.2)	0.59
Albite (heat-treated)	Na(AlSi3O8)	01-089-6427	---	115	15	30.5 (0.4)	0.64
Muscovite 2M1	K0.86Al1.94(Al0.965Si2.895C	01-086-1385	---	92	16	32.9 (0.9)	0.44

XRF(Wt%): K2O=6.7%, SiO2=65.5%, Al2O3=22.0%, Na2O=3.6%

Refinement Converged (R/E=1.78), ♣ Round=4, Iter=5, P=60, R=7.81% (E=4.39%, EPS=0.5)







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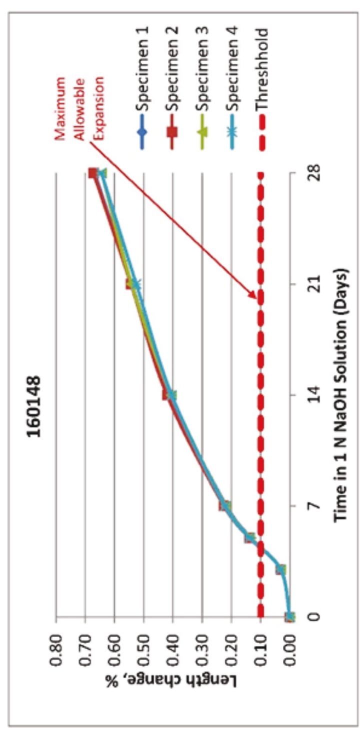
Appendix C: ASTM C1260 Summary Reports

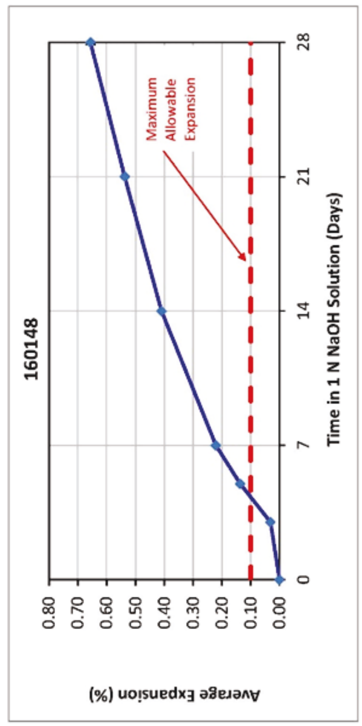
M1: CMB 160148 ASTM C1260 Report

Test Specification: ASTM C1260, Potential Alkali Reactivity of Aggregates
Material Description: CMB #160148 crushed to test gradations was tested with Holcim Cement CMB 160156

Exposure Condition	Date (M/D/Yr)	[1]Age (Day)	Specimen 1			Specimen 2			Specimen 3			Specimen 4			Average Expansion (%)	Standard Deviation (%)
			Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)		
Cast Date	7/12/2017		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Initial	7/13/2017		-0.0147			-0.0054			-0.0110			-0.0078				
[2]Zero read (80°C H_2O)	9/16/2016	0	-0.0076	0.0000	0.0000	0.0015	0.0000	0.0000	-0.0041	0.0000	0.0000	-0.0009	0.0000	0.0000	0.0000	0.0000
[3](80°C 1N NaOH)	9/19/2016	3	-0.0045	0.0031	0.0310	0.0046	0.0031	0.0310	-0.0010	0.0031	0.0310	0.0023	0.0032	0.0320	0.0313	0.0005
(80°C 1N NaOH)	9/21/2016	5	0.0058	0.0134	0.1340	0.0154	0.0139	0.1390	0.0095	0.0136	0.1360	0.0129	0.0138	0.1380	0.1368	0.0022
(80°C 1N NaOH)	9/23/2016	7	0.0141	0.0217	0.2170	0.0240	0.0225	0.2250	0.0179	0.0220	0.2200	0.0213	0.0222	0.2220	0.2210	0.0034
(80°C 1N NaOH)	9/30/2016	14	0.0333	0.0409	0.4090	0.0435	0.0420	0.4200	0.0364	0.0405	0.4050	0.0395	0.0404	0.4040	0.4095	0.0073
(80°C 1N NaOH)	10/7/2016	21	0.0465	0.0541	0.5410	0.0558	0.0543	0.5430	0.0500	0.0541	0.5410	0.0516	0.0525	0.5250	0.5375	0.0084
(80°C 1N NaOH)	10/14/2016	28	0.0591	0.0667	0.6670	0.0686	0.0671	0.6710	0.0602	0.0643	0.6430	0.0635	0.0644	0.6440	0.6563	0.0148

Notes:
[1]Age (day) represents testing age.
[2] All expansion values use the zero reading (specimen age, 48 hrs). Mortar bar readings are taken after 24 hours exposed to 80° C water.
[2] Mortar bars are moved into 80° C 1N NaOH solution after the zero readings for remaining test duration.





M2: CMB 160136 ASTM C1260 Report

Test Specification ASTM C1260, Potential Alkali Reactivity of Aggregates

Material Description CMB #160136 crushed to test gradations was tested with Holcim Cement CMB 160156

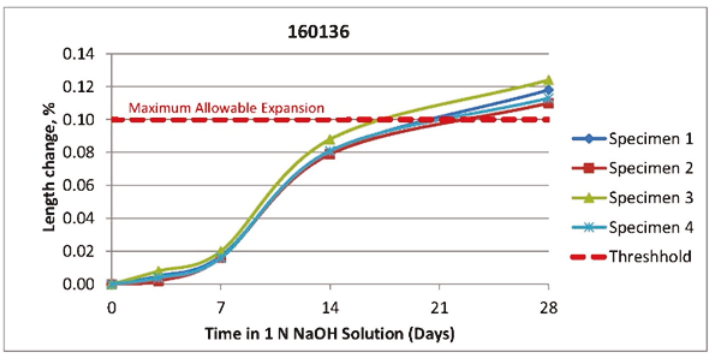
Exposure Condition	Date (M/D/Yr)	[1]Age (Day)	Specimen 1 Reading (in.)	Specimen 1 Change (in.)	Specimen 1 Expansion (%)	Specimen 2 Reading (in.)	Specimen 2 Change (in.)	Specimen 2 Expansion (%)	Specimen 3 Reading (in.)	Specimen 3 Change (in.)	Specimen 3 Expansion (%)	Specimen 4 Reading (in.)	Specimen 4 Change (in.)	Specimen 4 Expansion (%)	Average Expansion (%)	Standard Deviation (%)
Cast Date	1/3/2017		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Initial	1/4/2017		-0.0024			-0.0690			-0.0110			-0.0067				
[2]Zero read (80°C H_2O)	1/5/2017	0	0.0042	0.0000	0.000	-0.0624	0.0000	0.0000	-0.0056	0.0000	0.0000	-0.0003	0.0000	0.000	0.0000	0.0000
[3](80°C 1N NaOH)	1/8/2017	3	0.0047	0.0005	0.005	-0.0622	0.0002	0.0020	-0.0048	0.0008	0.0080	0.0001	0.0004	0.004	0.0048	0.0025
(80°C 1N NaOH)	1/12/2017	7	0.0059	0.0017	0.017	-0.0608	0.0016	0.0160	-0.0036	0.0020	0.0200	0.0013	0.0016	0.016	0.0173	0.0019
(80°C 1N NaOH)	1/19/2017	14	0.0122	0.0080	0.080	-0.0545	0.0079	0.0790	0.0032	0.0088	0.0880	0.0078	0.0081	0.081	0.0820	0.0041
(80°C 1N NaOH)	2/2/2017	28	0.0160	0.0118	0.118	-0.0514	0.0110	0.1100	0.0068	0.0124	0.1240	0.0110	0.0113	0.113	0.1163	0.0061

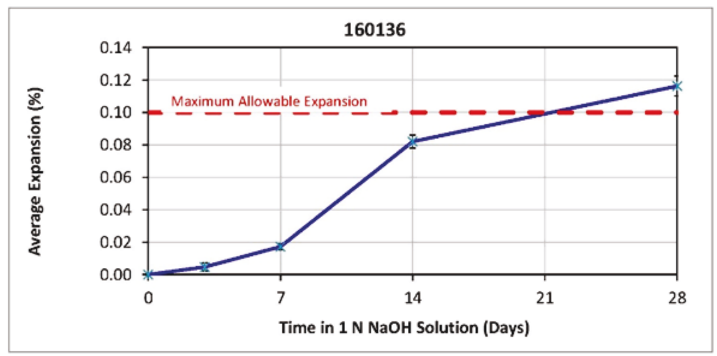
Notes:

[1]Age (day) represents testing age.

[2] All expansion values use the zero reading (specimen age, 48 hrs). Mortar bar readings are taken after 24 hours exposed to 80° C water.

[3] Mortar bars are moved into 80° C 1N NaOH solution after the zero readings for remaining test duration.

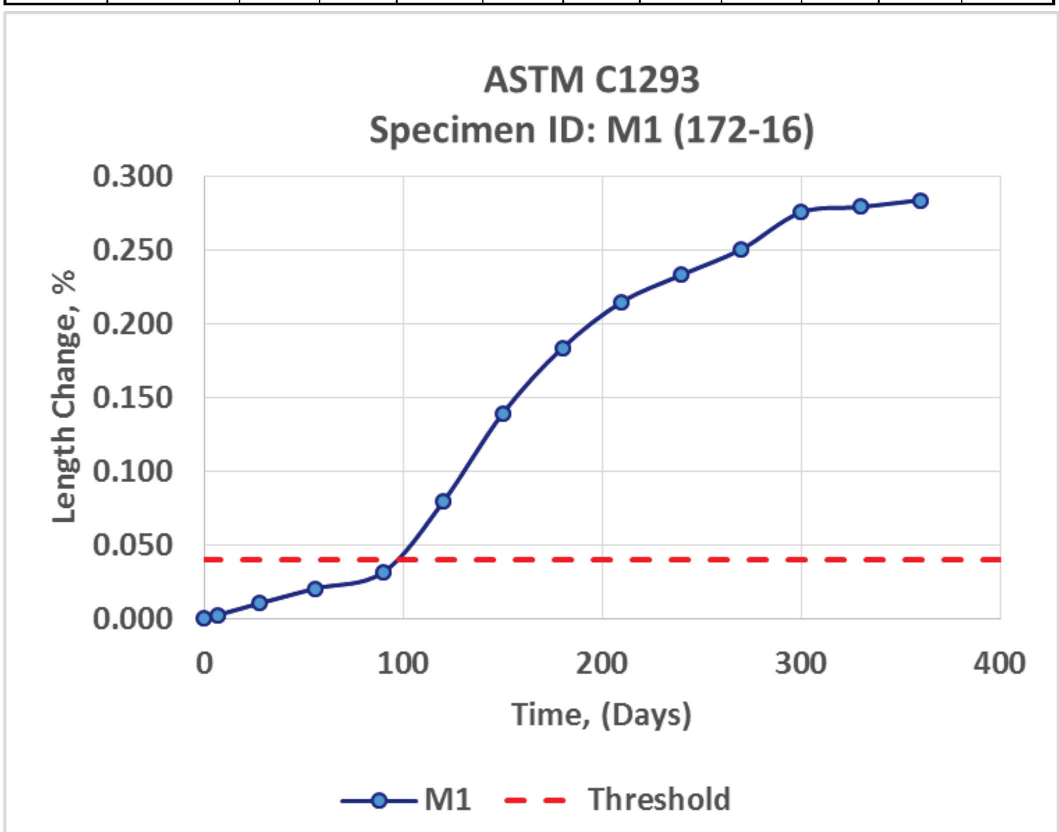




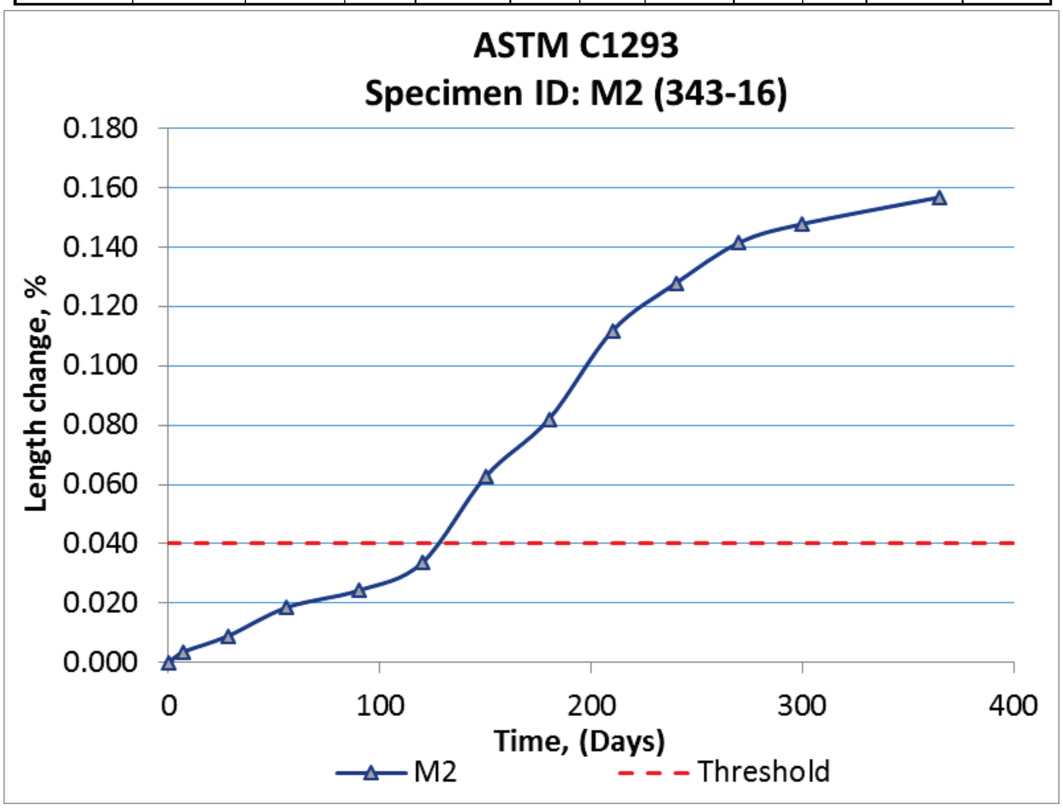
Appendix D: ASTM C1293 Summary Reports

M1: CMB 160148 ASTM C1293 Results

Length Change due to Alkali Reactivity of Aggregates, ASTM C 1293											
Mixture:	M1 (172-16)										
Test Coarse Aggregate:	CMB 160148										
Non-Reactive Aggregate:	Green Brothers Sand (Non Reactive)										
Portland Cement:	Holcim Type I/II										
Alkali Content:	0.54%, boosted to 1.25%										
Curing Condition:	Sealed at 38° C										
		Specimen 1			Specimen 2			Specimen 3			Average
Concrete Age (day)	Date	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Expansion (%)
Mix	6/22/2016	-	-	-		-	-		-	-	-
0	6/23/2016	-0.0048	-	-	-0.0070	-	-	-0.0080	-	-	0.000
7	6/30/2016	-0.0048	0.0000	0.0000	-0.0061	0.0009	0.0090	-0.0081	-0.0001	-0.0010	0.003
28	7/21/2016	-0.0042	0.0006	0.0060	-0.0058	0.0012	0.0120	-0.0066	0.0014	0.0140	0.011
56	8/18/2016	-0.0025	0.0023	0.0230	-0.0051	0.0019	0.0190	-0.006	0.0020	0.0200	0.021
90	9/21/2016	-0.0018	0.0030	0.0300	-0.004	0.0030	0.0300	-0.0045	0.0035	0.0350	0.032
120	10/21/2016	0.003	0.0078	0.0780	0.001	0.0080	0.0800	0	0.0080	0.0800	0.079
150	11/20/2016	0.0086	0.0134	0.1340	0.0073	0.0143	0.1430	0.0061	0.0141	0.1410	0.139
180	12/20/2016	0.0141	0.0189	0.1890	0.0118	0.0188	0.1880	0.0094	0.0174	0.1740	0.184
210	1/19/2017	0.0169	0.0217	0.2170	0.0154	0.0224	0.2240	0.0124	0.0204	0.2040	0.215
240	2/18/2017	0.0202	0.0250	0.2500	0.0158	0.0228	0.2280	0.0142	0.0222	0.2220	0.233
270	3/20/2017	0.0211	0.0259	0.2590	0.0186	0.0256	0.2560	0.0157	0.0237	0.2370	0.251
300	4/19/2017	0.0229	0.0277	0.2770	0.0201	0.0271	0.2710	0.0199	0.0279	0.2790	0.276
330	5/19/2017	0.0229	0.0277	0.2770	0.0206	0.0276	0.2760	0.0205	0.0285	0.2850	0.279
360	6/18/2017	0.0231	0.0279	0.2790	0.0216	0.0286	0.2860	0.0207	0.0287	0.2870	0.284



Length Change due to Alkali Reactivity of Aggregates, ASTM C 1293											
Mixture:	M2 (343-16)										
Test Coarse Aggregate:	CMB# 160136										
Non-Reactive Aggregate:	Green Brothers Sand (Non Reactive)										
Portland Cement:	Holcim Type I/II										
Alkali Content:	0.54%, boosted to 1.25%										
Curing Condition:	Sealed at 38° C										
		Specimen 1			Specimen 2			Specimen 3			Average
Concrete Age (day)	Date	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Expansion (%)
Mix	12/8/2016	-	-	-	-	-	-	-	-	-	-
0	12/9/2016	-0.0211	-	-	0.0023	-	-	-0.0046	-	-	0.00
7	12/16/2016	-0.0205	0.0006	0.0060	0.0025	0.0002	0.0020	-0.0043	0.0003	0.0030	0.004
28	1/6/2017	-0.0205	0.0006	0.0060	0.0034	0.0011	0.0110	-0.0036	0.0010	0.0100	0.009
56	2/3/2017	-0.0195	0.0016	0.0160	0.0042	0.0019	0.0190	-0.0025	0.0021	0.0210	0.019
90	3/9/2017	-0.0189	0.0022	0.0220	0.0046	0.0023	0.0230	-0.0018	0.0028	0.0280	0.024
120	4/8/2017	-0.0182	0.0029	0.0290	0.0053	0.0030	0.0300	-0.0004	0.0042	0.0420	0.034
150	5/8/2017	-0.0155	0.0056	0.0560	0.0079	0.0056	0.0560	0.003	0.0076	0.0760	0.063
180	6/7/2017	-0.0144	0.0067	0.0670	0.0096	0.0073	0.0730	0.006	0.0106	0.1060	0.082
210	7/7/2017	-0.0116	0.0095	0.0950	0.0126	0.0103	0.1030	0.0091	0.0137	0.1370	0.112
240	8/6/2017	-0.01	0.0111	0.1110	0.014	0.0117	0.1170	0.0109	0.0155	0.1550	0.128
270	9/5/2017	-0.009	0.0121	0.1210	0.0156	0.0133	0.1330	0.0124	0.0170	0.1700	0.141
300	10/5/2017	-0.0086	0.0125	0.1250	0.016	0.0137	0.1370	0.0135	0.0181	0.1810	0.148
365	12/8/2017	-0.0069	0.0142	0.1420	0.0163	0.0140	0.1400	0.0142	0.0188	0.1880	0.157

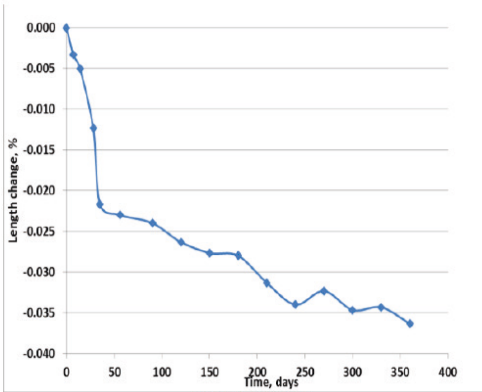


Appendix E: Sealed Cores

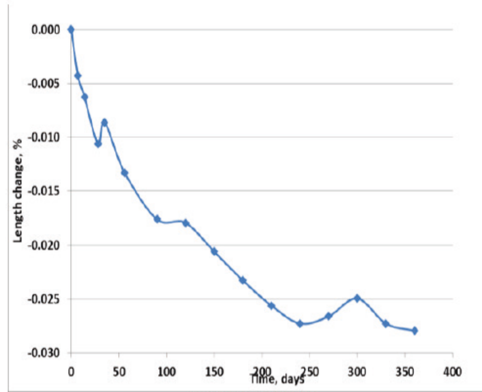
Summary of average expansions under sealed test conditions.

Specimen Age (Days)	Temperature							
	23 °C		38 °C		60 °C		80 °C	
	M1	M2	M1	M2	M1	M2	M1	M2
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.0033	-0.0120	-0.0043	0.0019	0.0122	0.0114	0.0135	0.0275
14	-0.0050	-0.0120	-0.0063	-0.0011	0.0062	0.0051	0.0088	0.0239
28	-0.0123	-0.0130	-0.0106	-0.0048	0.0025	0.0047	0.0065	0.0162
35	-0.0217	-0.0120	-0.0086	-0.0021	-0.0008	0.0034	0.0042	0.0122
56	-0.0230	-0.0060	-0.0133	-0.0058	-0.0068	0.0017	-0.0018	0.0065
90	-0.0240	-0.0067	-0.0176	-0.0071	-0.0128	-0.0033	-0.0112	-0.0025
120	-0.0263	-0.0083	-0.0179	-0.0078	-0.0178	-0.0066	-0.0182	-0.0091
150	-0.0277	-0.0110	-0.0206	-0.0075	-0.0222	-0.0083	-0.0258	-0.0155
180	-0.0280	-0.0110	-0.0233	-0.0135	-0.0278	-0.0126	-0.0318	-0.0195
210	-0.0313	-0.0133	-0.0256	-0.0151	-0.0345	-0.0153	-0.0352	-0.0218
240	-0.0340	-0.0173	-0.0273	-0.0168	-0.0382	-0.0146	-0.0322	-0.0231
270	-0.0323	-0.0193	-0.0266	-0.0148	-0.0415	-0.0189	-0.0385	-0.0248
300	-0.0347	-0.0180	-0.0249	-0.0141	-0.0362	-0.0159	-0.0532	-0.0228
330	-0.0343	-0.0170	-0.0273	-0.0151	-0.0392	-0.0183	-0.0625	-0.0321
360	-0.0363	-0.0167	-0.0279	-0.0155	-0.0432	-0.0239	-0.0625	-0.0408

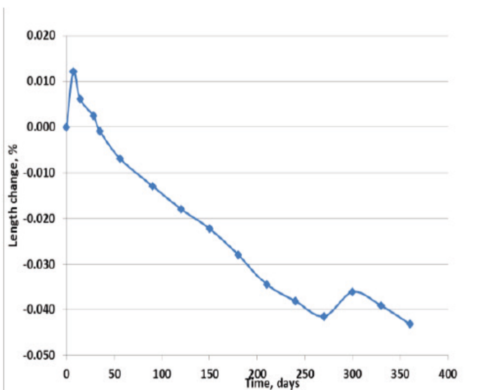
Summary of sealed core graphs for M1 aggregate:



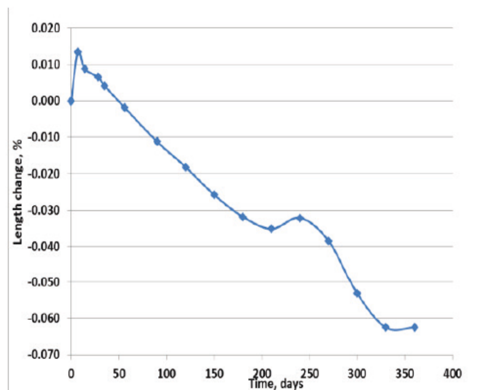
a) M1, 23⁰C



b) M1, 38⁰C

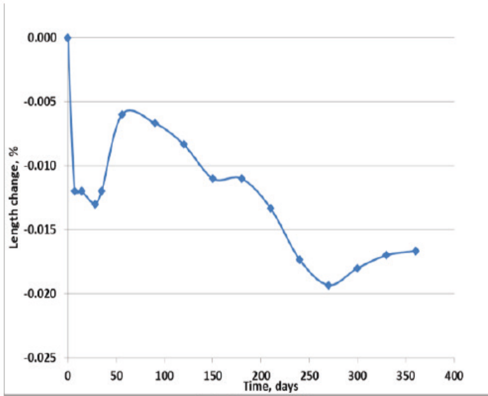


c) M1, 60⁰C

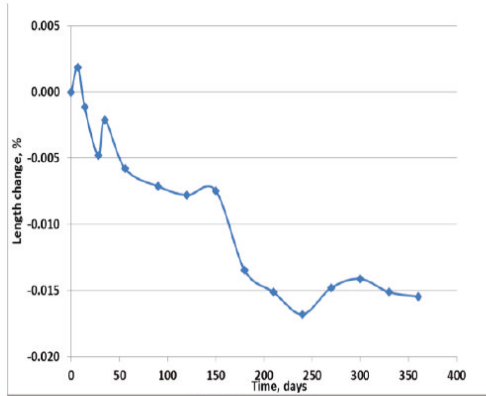


d) M1, 80⁰C

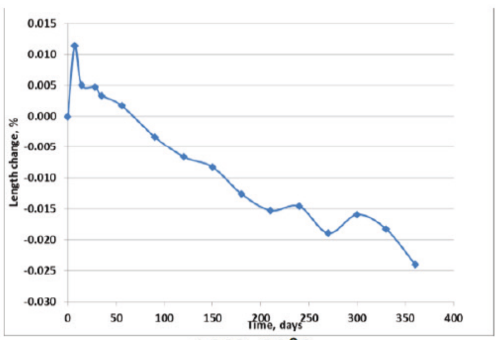
Summary of sealed core graphs for M2 aggregate:



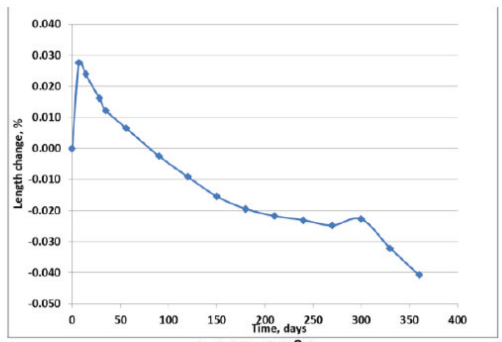
a) M2, 23°C



b) M2, 38°C



c) M2, 60°C



d) M2, 80°C

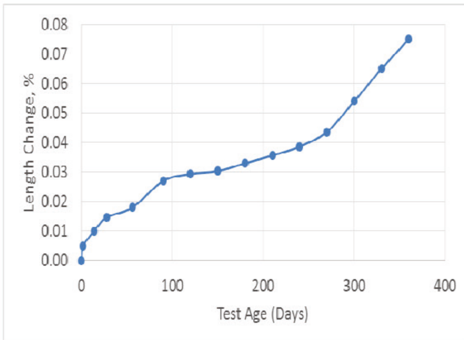
Appendix F: Modified ASTM C1260

Summary of average expansions under modified ASTM C1260 test conditions:

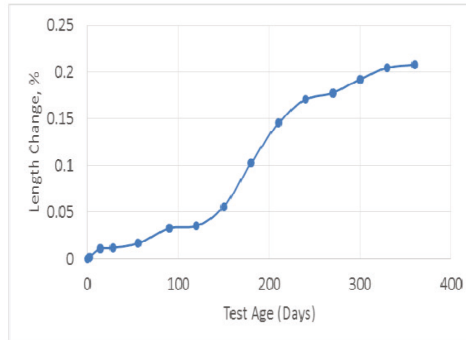
Specimen Age (Days)	Temperature							
	23 °C		38 °C		60 °C		80 °C	
	M1	M2	M1	M2	M1	M2	M1	M2
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.005	0.005	0.002	0.004	0.004	0.002	0.021	0.006
7	0.009	0.008	0.004	0.005	0.003	0.003	0.016	0.056
14	0.010	0.009	0.011	0.008	0.006	0.008	0.024	0.099
28	0.015	0.016	0.012	0.033	0.012	0.017	0.032	0.126
56	0.018	0.023	0.017	0.067	0.055	0.066	0.055	0.171
90	0.027	0.024	0.033	0.075	0.095	0.153		0.239
120	0.029	0.026	0.033	0.080	0.104	0.207		0.252
150	0.030	0.026	0.056	0.093	0.143	0.263	0.174	0.287
180	0.033	0.028	0.103	0.139	0.161	0.308	0.191	0.337
210	0.036	0.032	0.145	0.165	0.187	0.364	0.227	0.374
240	0.039	0.038	0.171	0.196	0.205	0.376	0.243	0.418
270	0.044	0.052	0.178	0.235	0.239	0.416	0.265	0.462
300	0.054	0.064	0.192	0.259	0.256	0.439	0.312	0.505
330	0.065	0.071	0.205	0.289	0.274	0.463	0.333	0.542
360	0.075	0.088	0.208	0.307	0.287	0.475	0.370	0.579

Readings for the 80C Gold Hills specimen at 90 and 120 days were invalid due to the evaporation of the NaOH solution.

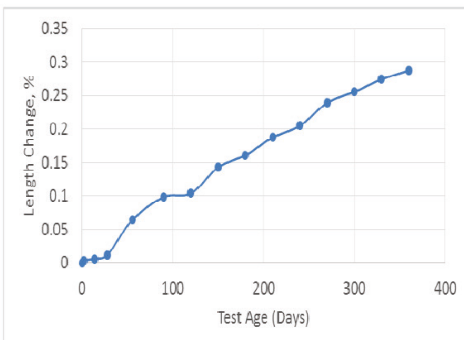
Summary of modified ASTM C1260 graphs for M1 aggregate:



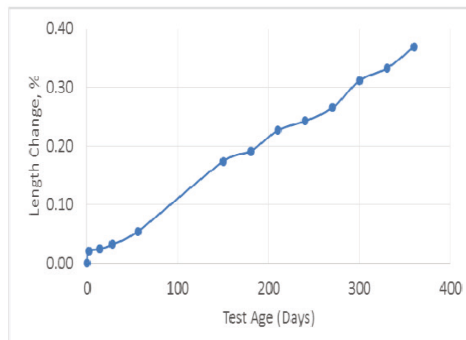
a) M1, 23^{0}C



b) M1, 38^{0}C

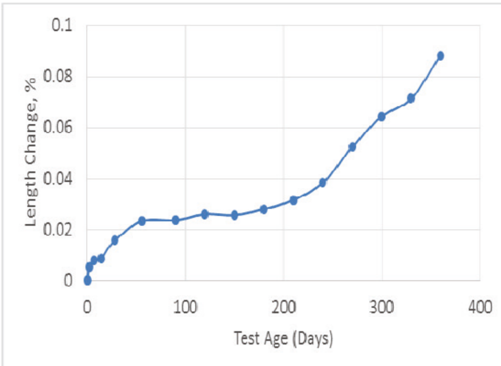


c) M1, 60^{0}C

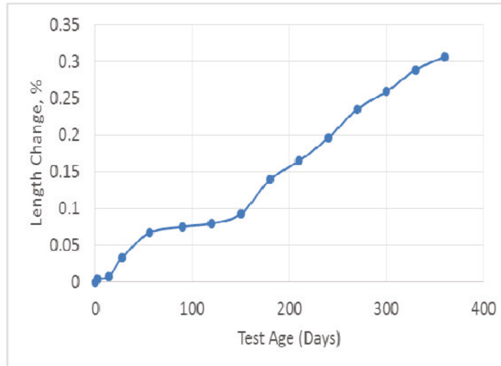


d) M1, 80^{0}C

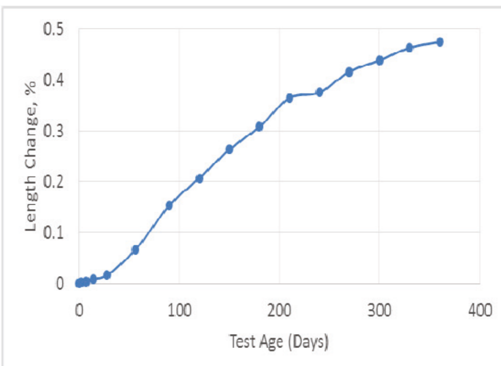
Summary of modified ASTM C1260 graphs for M2 aggregate:



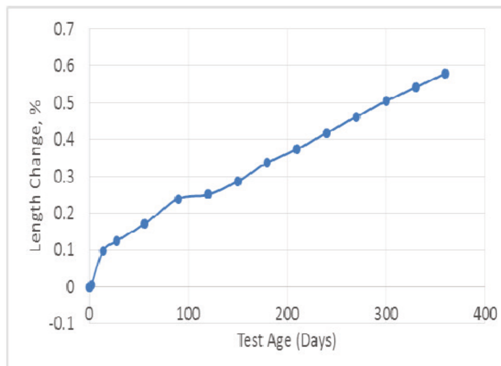
a) M2, 23⁰C



b) M2, 38⁰C



c) M2, 60⁰C



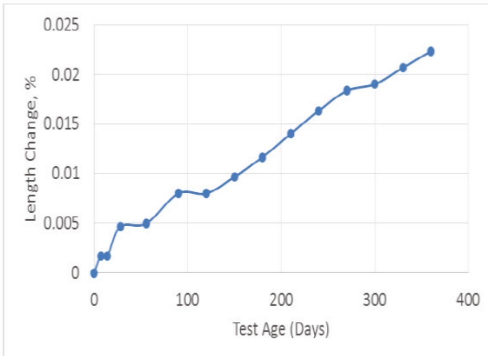
d) M2, 80⁰C

Appendix G: Modified ASTM C1293

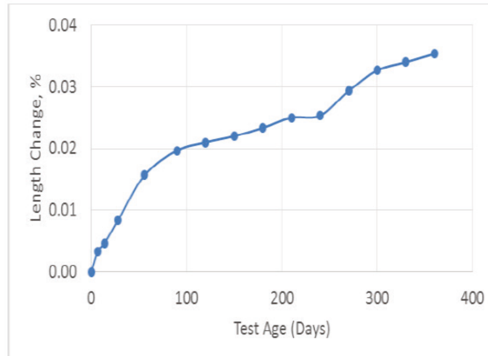
Summary of average expansions under modified ASTM C1293 test conditions.

Specimen Age (Days)	Temperature							
	23 °C		38 °C		60 °C		80 °C	
	M1	M2	M1	M2	M1	M2	M1	M2
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0030	0.0017	0.0027	0.0033	0.0053	0.0095	0.0120	0.0193
14	0.0047	0.0017	0.0053	0.0047	0.0090	0.0140	0.0210	0.0305
28	0.0050	0.0047	0.0083	0.0083	0.0160	0.0160	0.0225	0.0315
56	0.0077	0.0050	0.0137	0.0157	0.0243	0.0280	0.0305	0.0370
90	0.0120	0.0080	0.0150	0.0197	0.0260	0.0305	0.0325	0.0390
120	0.0133	0.0080	0.0163	0.0210	0.0253	0.0275	0.0340	0.0383
150	0.0140	0.0097	0.0170	0.0220				
180	0.0157	0.0117	0.0193	0.0233				
210	0.0170	0.0140	0.0213	0.0250				
240	0.0180	0.0163	0.0217	0.0253				
270	0.0180	0.0183	0.0233	0.0293				
300	0.0180	0.0190	0.0243	0.0327				
330	0.0183	0.0207	0.0247	0.0340				
360	0.0193	0.0223	0.0257	0.0353				

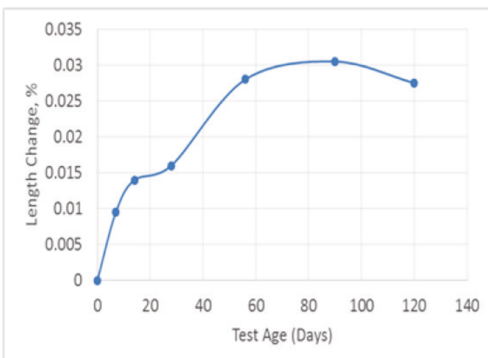
Summary of modified ASTM C1293 graphs for M1 aggregate:



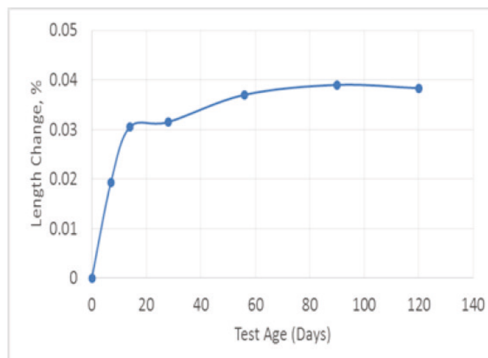
a) M1, 23⁰C



b) M1, 38⁰C

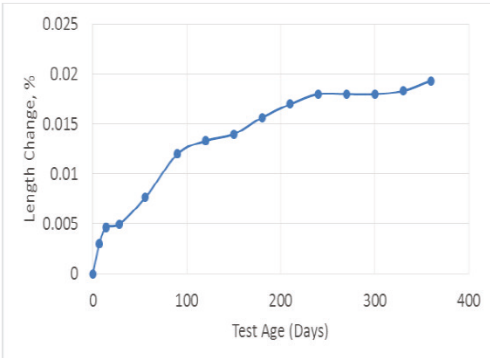


c) M1, 60⁰C

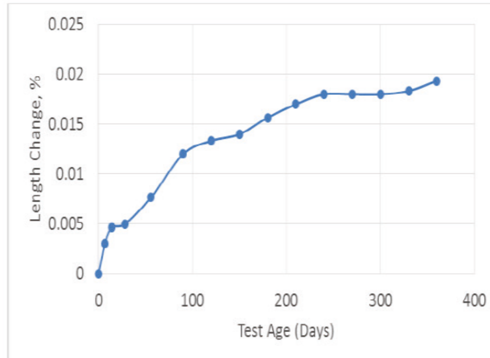


d) M1, 80⁰C

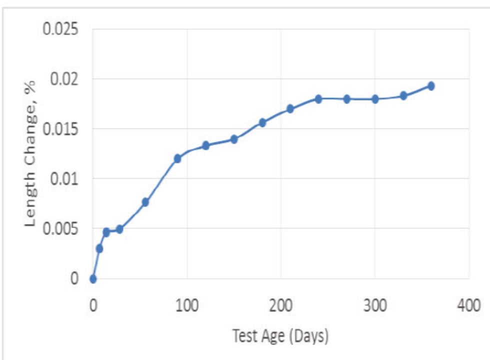
Summary of modified ASTM C1293 graphs for M2 aggregate:



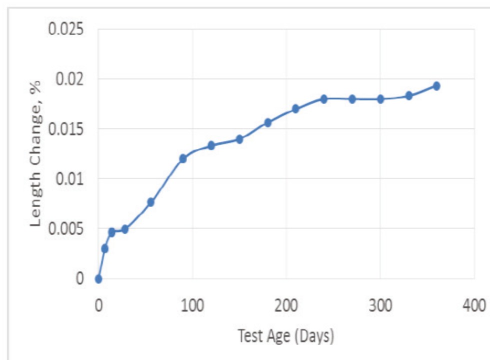
a) M2, 23ºC



b) M2, 38ºC



c) M2, 60ºC



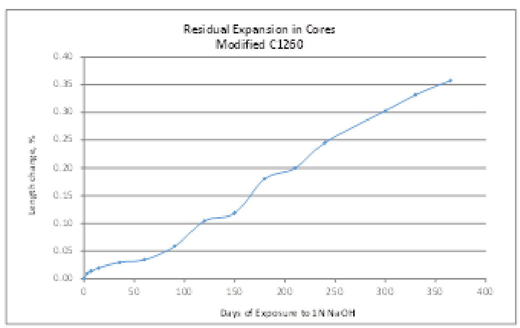
d) M2, 80ºC

Appendix H: Effect of Extended Conditioning

M1: CMB 160148

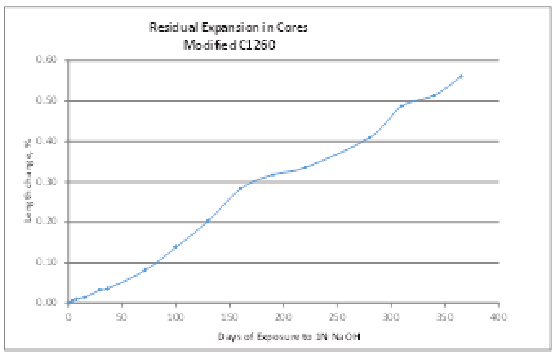
M1

Residual Expansion Measurements in Cores														
Test Aggregate:	CMB 160148													
Mixture Identification:	M1													
Environmental Condition:	Cured in ambient air environment approximately 4 months, then water saturated at 23°C for 35 days before cores were submerged in 1N NaOH													
Temperature:	80°C													
		Core 1			Core 2			Core 3			Core 4			Average
Exposure Age (day)	Date	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Expansion (%)
Initial	1/30/2017	0.1516	-	-	0.0301	-	-	0.104	-	-	0.0981	-	-	-
0	1/31/2017	0.1609	0.0000	0.0000	0.0403	0.0000	0.0000	0.1159	0.0000	0.0000	0.1059	0.0000	0.0000	0.0000
3	2/3/2017	0.1617	0.0008	0.0080	0.041	0.0007	0.0070	0.117	0.0011	0.0110	0.1072	0.0013	0.0130	0.0098
7	2/7/2017	0.1626	0.0017	0.0170	0.0413	0.0010	0.0100	0.1172	0.0013	0.0130	0.1075	0.0016	0.0160	0.0140
14	2/14/2017	0.1626	0.0017	0.0170	0.0416	0.0013	0.0130	0.1179	0.0020	0.0200	0.1087	0.0028	0.0280	0.0195
35	3/7/2017	0.1662	0.0053	0.0530	0.0426	0.0023	0.0230	0.1193	0.0034	0.0340	0.1066	0.0007	0.0070	0.0293
60	4/4/2017	0.1589	0.0020	0.0200	0.0436	0.0033	0.0330	0.119	0.0041	0.0410	0.11	0.0041	0.0410	0.0338
90	5/2/2017	0.1645	0.0036	0.0360	0.0478	0.0075	0.0750	0.1205	0.0046	0.0460	0.1135	0.0076	0.0760	0.0583
120	5/30/2017	0.167	0.0061	0.0610	0.057	0.0167	0.1670	0.1241	0.0082	0.0820	0.1167	0.0108	0.1080	0.1045
150	6/27/2017	0.1692	0.0083	0.0830	0.0538	0.0135	0.1350	0.1269	0.0110	0.1100	0.1204	0.0145	0.1450	0.1183
180	7/25/2017	0.1672	0.0063	0.0630	0.0608	0.0205	0.2050	0.1323	0.0164	0.1640	0.1232	0.0173	0.1730	0.1807
210	8/22/2017	0.1778	0.0169	0.169	0.0598	0.0195	0.195	0.1361	0.0202	0.202	0.1291	0.0232	0.2320	0.1995
240	9/19/2017	0.1856	0.0247	0.247	0.063	0.0227	0.227	0.1393	0.0234	0.234	0.1334	0.0275	0.2750	0.2458
300	11/14/2017	0.194	0.0331	0.331	0.0736	0.0333	0.333	0.1414	0.0255	0.255	0.1353	0.0294	0.2940	0.3033
330	12/12/2017	0.196	0.0351	0.351	0.0745	0.0342	0.342	0.1466	0.0307	0.307	0.1386	0.0327	0.3270	0.3318
365	1/9/2018	0.2001	0.0392	0.392	0.076	0.0357	0.357	0.1499	0.0340	0.34	0.1402	0.0343	0.343	0.358



M2: CMB 160136

Residual Expansion Measurements in Cores											
Test Aggregate:		CMB 160136									
Mixture Identification:		M2									
Environmental Condition:		Cured in ambient air environment approximately 4 months, then water saturated at 23°C for 35 days before cores were submerged in 1N NaOH									
Temperature:		80°C									
		Core 1			Core 2			Core 3			Average
Exposure Age (day)	Date	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Reading (in.)	Change (in.)	Expansion (%)	Expansion (%)
Initial	12/12/2016	0.0211	-	-	0.0307	-	-	0.014	-	-	-
0	12/13/2016	0.0272	0.0000	0.0000	0.0381	0.0000	0.0000	0.0206	0.0000	0.0000	0.0000
3	12/16/2016	0.0273	0.0001	0.0010	0.0388	0.0007	0.0070	0.0213	0.0007	0.0070	0.0050
7	12/20/2016	0.0277	0.0005	0.0050	0.039	0.0009	0.0090	0.022	0.0014	0.0140	0.0093
15	12/28/2016	0.0282	0.0010	0.0100	0.0392	0.0011	0.0110	0.0227	0.0021	0.0210	0.0140
29	1/11/2016	0.0302	0.0030	0.0300	0.0406	0.0025	0.0250	0.0247	0.0041	0.0410	0.0320
36	1/18/2017	0.0307	0.0035	0.0350	0.0395	0.0014	0.0140	0.0262	0.0056	0.0560	0.0350
71	2/22/2017	0.0337	0.0065	0.0650	0.0476	0.0095	0.0950	0.0287	0.0081	0.0810	0.0803
100	3/21/2017	0.0342	0.0070	0.0700	0.058	0.0199	0.1990	0.0352	0.0146	0.1460	0.1383
130	4/18/2017	0.0444	0.0172	0.1720	0.0595	0.0214	0.2140	0.043	0.0224	0.2240	0.2033
160	5/16/2017	0.0555	0.0283	0.2830	0.0624	0.0243	0.2430	0.053	0.0324	0.3240	0.2833
190	6/13/2017	0.0599	0.0327	0.3270	0.0711	0.0330	0.3300	0.0502	0.0296	0.2960	0.3177
220	7/11/2017	0.0607	0.0335	0.3350	0.0725	0.0344	0.3440	0.0533	0.0327	0.3270	0.3353
280	9/5/2017	0.0624	0.0352	0.3520	0.0802	0.0421	0.4210	0.0663	0.0457	0.4570	0.4100
310	10/3/2017	0.0695	0.0423	0.4230	0.0883	0.0502	0.5020	0.0745	0.0539	0.5390	0.4880
340	10/31/2017	0.0729	0.0457	0.4570	0.0906	0.0525	0.5250	0.0765	0.0559	0.5590	0.5137
365	11/28/2017	0.0763	0.0491	0.4910	0.0953	0.0572	0.5720	0.0826	0.0620	0.6200	0.5610



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Monica A. Ramsey, Stephanie G. Wood, and Robert D. Moser

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14. ABSTRACT

The objective of this study was to develop methods to sample and test residual alkali-silica reaction-induced expansion capacity of in-situ concrete using cores tested in accelerated environments. The effect of alkali-silica reaction on the mechanical properties of concrete was also investigated in order to more accurately predict the remaining service life of existing concrete structures. Residual expansion measurements were taken up to 12 months on cores drilled from large concrete blocks produced with two different reactive aggregates and stored in various exposure conditions at different temperatures. The three exposure conditions were sealed, stored in NaOH solution, and stored over water. The four temperatures were 23, 38, 60, and 80ºC. Compressive strength, splitting tensile strength, and modulus of elasticity were measured for cylinders immersed in NaOH at 80°C up to 56 days to generate correlations between ASR damage and mechanical properties. For unboosted cores, the 80°C modified conditioning regime appeared to be the most effective in producing significant residual expansion in a short period of time. Late-age conditioning had essentially no impact on the expansion of cores at one year. Modulus of elasticity was influenced most and was more accurately captured by delaying conditioning.

15. SUBJECT TERMS
Concrete, Alkali-silica reaction, Expansion, ASR, Damage, Strength, Service life modeling, Alkali-aggregate reactions, Concrete, Concrete--Expansion and contraction, Concrete--Testing

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