MOUNTAIN-PLAINS CONSORTIUM

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Risk of Alkali-Silica Reaction When Using Recycled Concrete Aggregate in New Concrete

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Risk of Alkali-Silica Reaction when Using Recycled Concrete Aggregate in New Concrete

Jennifer Tanner, PhD, FACI
Mr. Bryce Fiore, EIT

University of Wyoming
Laramie, WY

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Our thanks and appreciation also go out to each of the participating laboratories whose time and effort allowed for a larger study, thereby increasing the significance of the data. They are listed below by study in alphabetical order:

Study 1 – RCA-S	Study 2 – RCA-BR and RCA-KR
CTL Group	Georgia Institute of Technology
Georgia Institute of Technology	Oregon State University
Oregon State University	Pennsylvania State University
Pennsylvania State University	Ryerson University
Ryerson University	University of Alabama
University of Alabama	University of New Brunswick
University of New Brunswick	University of Texas
University of Texas	University of Wyoming
University of Wyoming	Wyoming Department of Transportation

The authors also recognize all the researchers who conducted the experiments on the natural Wyoming aggregates to allow for such comprehensive examination.

Disclaimer

ABSTRACT

Two interlaboratory studies were performed utilizing recycled concrete aggregate (RCA) in accordance with ASTM C1260 Accelerated Mortar Bar Test (AMBT) in addition to the previous study documented in Adams et al. 2013. The first round of testing utilized a non-laboratory created RCA and the second evaluated two Wyoming concretes prepared with Black Rock and Knife River aggregates respectively. It was discovered that concrete made with RCA exhibits lower expansions due to ASR than the original concrete made with natural aggregates. Furthermore, RCA as it applies to ASTM C1260, has been observed to exceed the repeatability and reproducibility limits set by ASTM C1260. The authors suggest that the precision statement within ASTM C1260 be modified in order to include RCA and account for this increased variability. Precision statements for both studies were conducted utilizing a minimum of nine laboratories.

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EXECUTIVE SUMMARY

One of the most utilized materials in the world is concrete. This simple mixture of cement, coarse and fine aggregate, and water is important to the building industry because it is highly sustainable, durable, and able to sustain loads. Unfortunately, some concretes are plagued by a chemical reaction known as alkali-silica reaction (ASR).

ASR is a process that causes a gel to form within the concrete matrix; it is highly expansive, hydrophilic, and hygroscopic. Ultimately, as ASR gel increases in volume it can cause premature cracking if the induced stresses exceed the concrete's tensile strength.

As world resources become scarce it is increasingly attractive to use recycled concrete aggregate (RCA) as a raw material in new concrete. This topic has been under investigation at the University of Wyoming (UW). Reusing concrete salvaged from demolition work could be the next big step in concrete design. However, effective use of RCA requires the ability to classify whether it is reactive in terms of ASR.

The premise of the study is that ASR, as a chemical reaction, will eventually consume the reactants and create an inert concrete. At UW, several large concrete field blocks have been cast with a variety of aggregates and varying ASR reactivity. A few of these blocks were cast with RCA. Over the years they have been measured under field conditions in order to catalogue the reaction across the aggregates. Some of these blocks have hence been broken and crushed into material suitable for the ASTM C1260 test, also known as the Accelerated Mortar Bar Tests (AMBT) and sent out as an interlaboratory study to a variety of universities across North America.

Two rounds of experimental testing were performed and presented within this report to expand upon a study documented in Adams et al. 2013; and Ideker et al. 2012a, 2014. In the first study, nine laboratories performed the AMBT with RCA from a demolished structure. The second study included 11 operators across 10 laboratories using RCA from demolished field blocks. The goal was to determine the repeatability of the AMBT and evaluate if RCA is more inert than the reactive natural aggregates. These studies additionally provide evidence toward the need to expand the range of the AMBT.

It was discovered that RCA in the AMBT exhibited decreased expansions compared with the associated AMBT with natural aggregate but displayed significant increases in the variability among test results. Therefore, it is suggested that ASTM C1260 modify the precision statement in order to properly include RCA as a possible test material.

1. INTRODUCTION

Concrete is one of the most widely used building materials in the world. It also provides a large source of waste during demolition of structures and roadways. A phenomenon that contributes toward premature demolition is known as Alkali-Silica Reaction (ASR). ASR is a long-term performance issue, and symptoms can appear as early as a few years or anytime thereafter in the service life of a structure. As such, minimizing it in the design phase of a structure is paramount to the structure's success. A potential solution for both sustainability in demolition and increased service life is repurposing concrete that is taken out of service, crushing it, and using it as recycled concrete aggregate (RCA). This material then allows for a more economical aggregate source for towns that are located far from any natural aggregate sources.

RCA is produced by crushing preexisting concrete into the appropriate sizes for engineering applications. During this process, reinforcing steel is removed. All that remains is the natural aggregate and the adhered cement paste. RCA has the reputation of being a substandard material due to lack of consolidated research regarding this material in current building practices. Ideker et al., 2014, confirmed this perception by conducting a survey about sustainable practices and the use of RCA through 26 different agencies across the United States including DOTs and the FHWA. While RCA as an effective building material is viewed with skepticism, it is possible that concrete which has been designed properly with RCA can meet or even exceed the current standards for concrete strength and durability (Adams et al. 2013). A major concern with using RCA as a sustainable building material is its potential for ASR, in particular if the concrete was removed from service due to ASR. As a building material, a full serviceability record is not always available. As such, RCA is usually handled with caution in structural work. Pairing the poor service record with a lack of consolidated knowledge about ASR in RCA has resulted in using RCA primarily as road base.

ASR was originally discovered and researched by Stanton in the 1940s. However, ASR still affects concrete today. ASR is a chemical reaction taking place in concrete between reactive forms of silica in the aggregate and the alkalis in the cement pore solution (Stanton 1940). This causes a gel to form within the cement paste matrix. This gel is hydrophilic, hygroscopic, and expansive. The expansion caused by the absorption of water within the gel in turn increases the pressure within the concrete until eventually the internal pressure surpasses the tensile strength of the concrete, resulting in cracking. Once this happens, the affected concrete is more susceptible to environmental factors, which can result in a direct path for moisture to infiltrate and be absorbed by the gel. This process exacerbates the cyclic nature of ASR damage.

The predominant process for identifying a reactive aggregate is utilizing ASTM C1260 "Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates," also known as the Accelerated Mortar Bar Test (AMBT). This allows for the identification of ASR within 16 days after casting. Despite how common this test is, it has known difficulties with properly identifying the field performance of the aggregate in question. It is known that the AMBT is very severe and can result in an overestimation of the reactivity of some aggregates (Touma 2001; Ideker et al. 2012b). Touma further suggests that the AMBT should only be used as a screening test, and not for rejecting an aggregate. In order to reject an aggregate, ASTM C1293 "Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction," also known as the Concrete Prism Test (CPT), should be used. Although the CPT is considered the most reliable test to identify ASR, this test requires a year to complete and two years if supplementary cementitious materials are used. Due to the long duration of the CPT, AMBTs and CPTs are often used in conjunction with each other. Unfortunately, the AMBT and the CPT can sometimes produce conflicting results (Lu et al. 2004; Thomas et al. 2006; Ideker et al. 2012b). The conflicting results are sometimes associated with the fact that the AMBT is only viable for fine aggregates, meaning that coarse aggregate has to get crushed to the proper size, which may lead to inaccurate reactivity predictions (Ideker et al. 2012b). Additionally, Ideker et al., 2012b, states there are even specific mineral compositions for which the AMBT may result in false negatives. The classifications from Kimble et al. (2015) in Table 4.4 also demonstrate differences between AMBT and CPT results. Most notably are the instances where the AMBT classified an aggregate as non-reactive, but the CPT classified it as moderately reactive. Something to note about both the AMBT and the CPT is that both tests were established based on test data from natural aggregates. This leaves their potential applicability toward RCA in question. Previous research in Adams et al., 2013, indicates that the AMBT for use with RCA is applicable, but produces a large amount of variability with repeat tests.

The studies presented within this report are an effort to address the reproducibility of AMBT results using RCA. These studies are also compared to available expansion data with field exposure blocks, CPT, and AMBTs utilizing natural aggregate or RCA.

2. BACKGROUND

In the 1980s the Wyoming Highway Department reconstructed approximately 28 miles of Interstate 80 between Cheyenne and the Nebraska state line. The pavement had failed prematurely due to alkali silica reactivity. Because the haul distance of aggregate was a significant factor in the reconstruction design, it was decided to evaluate recycling the existing pavement into the new concrete. An extensive study was conducted with the David Stark of the Portland Cement Association, and ASTM C227 was utilized at that time. The pavement was recycled using 65% recycled coarse aggregate and 25% recycled fine aggregate. The oldest section has now been in place for 30 years. This research directly impacts how WYDOT will evaluate RCA for ASR in the future.

The studies presented within this paper are intended to expand on a previous study on the effects of ASR with RCA that is presented in Adams et al., 2013. Throughout this article, the authors highlight three levels of insufficient knowledge surrounding the use of RCA:

1. The reproducibility of individual test results
2. The effect of crushing procedures on measured reactivity due to changes in particle composition during the crushing phase
3. The reliability of results when compared to other ASR testing procedures and results from field exposure

Within Adams et al., 2013, two phases of testing were conducted to examine the first two points including the applicability of the current ASTM C1260 test method for detecting RCA reactivity due to ASR. The first phase utilized four laboratories and four laboratory created RCAs using crushed outdoor exposure blocks that were used in a long-term aggregate alkali-silica reactivity testing and correlation study performed at CANMET in Ottawa, Ontario. This first phase specifically investigated the effects of crushing procedure on the reactivity of RCA when tested using ASTM C1260. The second phase consisted of two laboratories and three stockpiled or demolished field RCAs. The first RCA, CalPort, came from breaking up concrete slabs produced from returned concrete at a ready-mix concrete facility in Oregon. The other two came from demolished structures that had some level of ASR damage on the UW campus. Sources included concrete steps and an indoor foundation of an old power plant. The Adams paper designates the Wyoming RCAs from the concrete steps as St-R and the indoor foundation as Op-R. This report designates these as RCA-S and RCA-OPP, respectively. An objective for the interlaboratory testing described in this report is to expand the number of participating laboratories and RCA sources considered in Adams et al. 2013.

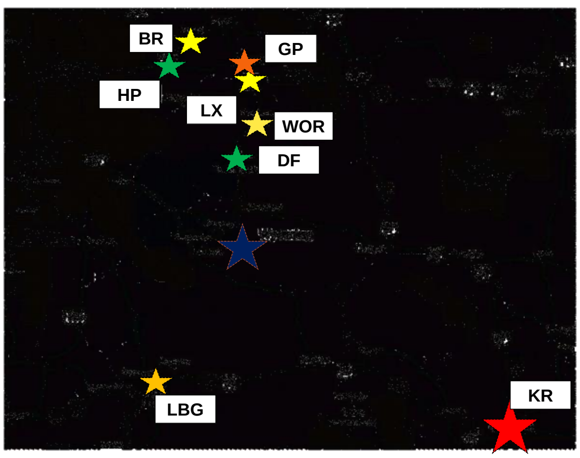
AMBTs on Wyoming natural aggregates were performed by Hacker and Fertig at the University of Wyoming. These researchers performed three tests according to ASTM C1260 to classify the reactivity of the aggregates and discern whether coarse, fine, or combined had differing levels of reactivity (Kimble et al. 2015). Additionally, CPT specimens for each Wyoming aggregate were cast using combined coarse and fines from the same pits. These tests are compared to the AMBT results for both RCA studies presented within this report.

3. MATERIALS AND METHODS

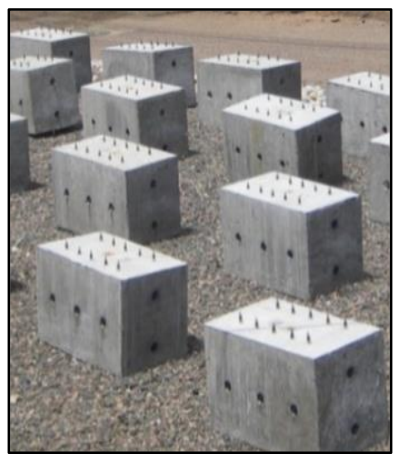
This project builds on previous work evaluating eight Wyoming aggregates with AMBT, CPT, and field exposure blocks monitoring long-term expansions (Kimble et al. 2015). A unique opportunity existed to evaluate four RCA sources using a multi-laboratory study. Three different RCAs were collected, processed, and shipped to independent laboratories. Cement was included within the shipment. AMBT testing was performed and results were returned to UW for analysis.

3.1 Aggregates

The eight Wyoming aggregates are: Black Rock (BR), Devries Farm Pit (DF), Goton Pit (GP), Harris Pit (HP), Knife River (KR), Labarge (LBG), Lamax (LX), and Worland (WOR). Locations and relative reactivity levels are presented in Figure 3.1a. A classification summary of this figure is given in Table 4.4. Aggregate from each of these pits have been cast into large field blocks as seen in Figure 3.1b. Throughout this paper the reactivity levels are represented as follows: NR = nonreactive, MR = moderately reactive, HR = highly reactive and VHR = very highly reactive.



a)



b)

Figure 3.1 a) Summary of Wyoming aggregates and reactivity. Note: Green=NR; yellow=MR; yellow-orange=MR/HR; red=HR. b) Field specimens at the University of Wyoming.

The aggregates used in the first AMBT interlaboratory study were RCA-S. This material was obtained from the University of Wyoming exterior steps on the south entrance of the B building that exhibited severe ASR damage. New material on the right end of the steps in Figure 3.2 replaced the material that became the RCA-S aggregate. Later the entire set of steps was added to the RCA stockpile. RCA-S and another source, Old Power Plant (RCA-OPP), have additionally been cast into large field blocks to better understand the reactivity of RCA under field conditions. RCA-S has been designated in Adams et al., 2013, and Ideker et al., 2012a, 2014, as St-R.

Figure 3.2 Wyoming steps used as aggregate for RCA-S study.

The aggregates used in the AMBT interlaboratory study utilized RCA created by crushing two field blocks. One field block was cast using natural aggregate from Black Rock and the other was cast using natural aggregate from Knife River.

3.2 Cement

The cement used for this study came from Holcim. The chemical composition is indicated in Table 3.1.

Table 3.1 Holcim type I/II cement chemical analysis

Chemical	Result (%)
Na_2O	0.186
K_2O	0.823
SiO_2	20.28
Al_2O_3	4.93
Fe_2O_3	3.28
SO_3	3.32
CaO	63.84
MgO	1.35
C_3S	58.52
C_2S	13.99
C_3A	7.52
C_4AF	9.97
Na_2O_{eq}	0.728

Where Na_2O_{eq} is the total equivalent alkalis within the cement and is $(\%Na_2O + 0.658 \cdot \%K_2O)$

3.3 Testing Program and Nomenclature

As an aid to the reader in keeping track of naming conventions used throughout this report, Table 3.2 is given listing each experiment with its abbreviated label, the aggregate used, and the corresponding section of this report. Table 3.2 also explains additional nomenclature used throughout this report.

Table 3.2 Testing program and nomenclature

Experiment		**Test Duration**	**Label**		**Aggregate**	**Reference Section**
Field Specimens		**Minimum 5 years**	BR, DF, GP, HP, KR, LBG, LX, WOR		Natural Wyoming Aggregates	0
			STEP-U	Unboosted RCA	RCA-S	
			STEP-B	Boosted RCA	RCA-S	
			OPP-B	Boosted RCA	RCA-OPP	
			CON-U	Unboosted Control	Non-Reactive	
CPT/ ASTM C1293	**AMBT/ ASTM C1260**	**One year/ 14 days**	BR, DF, GP, HP, KR, LBG, LX, WOR		Natural Wyoming Aggregates	0/0
RCA AMBT		**14 days, extended to 28**	RCA-20S		20% RCA-S 80% non-reactive	0
			RCA-50S		50% RCA-S 50% non-reactive	
			RCA-20BR		20% RCA-Black Rock 50% non-reactive	
			RCA-50BR		50% RCA-Black Rock 50% non-reactive	
			RCA-20KR		20% RCA-Knife River 50% non-reactive	
			RCA-50KR		50% RCA-Knife River 50% non-reactive	
Extra Nomenclature		RCA-S	Aggregate from demolished Wyoming patio			
		RCA Black Rock	Black Rock aggregate that was cast into a field block, then used as RCA			
		RCA Knife River	Knife River aggregate that was cast into a field block, then used as RCA			
		St-R.	Adams designation of RCA-S			
		Op-R	Adams designation of RCA-OPP			
		CalPort	Aggregate from Oregon ready-mix concrete facility			
Classification		NR	Nonreactive			
		MR	Moderately reactive			
		HR	Highly reactive			
		VHR	Very highly reactive			

3.4 Field Specimen Overview

Although less commonly performed due to the amount of space required, large scale field testing of ASR has been a priority at UW because these specimens most closely represent field performance. Originally cast in 2008, these specimens are used to study ASR expansions for critical Wyoming aggregates. Predicting how an aggregate responds to real world conditions is the goal of testing for ASR. Field specimens best reflect the behavior of an aggregate in the specific concrete mix. Given sufficient time, field expansions lead to an accurate measure of aggregate reactivity and can serve as a benchmark for other accelerated tests. This is because AMBT and CPT are both accelerated tests, and are carefully monitored in a controlled environment, which limits their ability to predict the true reactivity of aggregates (Ideker et al. 2012b). The lack of control in environmental exposure to the field specimens makes understanding all the factors that go into ASR difficult. However, each of those factors affect concrete used in the real world, and that is where the true value of the field specimens begin to emerge.

The blocks rest on ¾-in. (19.5 mm) minus angular gravel atop a bed of 4-in. (101.6 mm) minus rock to ensure a level surface and properly drained foundation. Each specimen was cast in 15 x 15 x 26 in. (380 x 380 x 660 mm) plywood forms. The forms were coated with a debonding agent and the edges and corners were caulked to prevent moisture loss during curing. Threaded steel inserts were utilized to create 12 measurement locations for each block.

Measurements are taken utilizing a Demec and are recorded to the nearest 0.001 mm. Care was taken to use the instrument in exactly the same manner every time. The device is created using invar to reduce thermal expansions. In addition, thermal effects based on ambient temperature were accounted for by recording the surface temperature at the time of recording and adjusting measurements to a constant 70°F (21℃); the coefficient of thermal expansion used was 5.5 x 10^{-6}/°F (11.7 x 10-6/℃). Twelve different measurements were taken and the average is presented as the total expansion of the block. Four longitudinal and two transverse measurements are on the top, two longitudinal measurements are along each side, and one vertical measurement is on the ends. Each measurement is repeated to ensure each span was measured properly.

Aggregate gradations for the each specimen was the same as the gradation of the as received aggregate from each source (Fertig et al. 2013). A polycarboxylate superplasticizer was utilized to achieve the desired workability. It has been studied and concluded that polycarboxylate superplasticizers have a negligible effect on concrete expansion due to ASR (Leemann et al. 2010). Generic material quantities are displayed in Table 3.3. Specific quantities of material for each specimen are displayed in Table A.1. At least one specimen from each aggregate source used NaOH to boost the cement alkalinity to a Na_2O_{eq} of 1.25% to represent an upper bound of the aggregate's reactive potential. More information can be found in Kimble et al., 2015.

Table 3.3 Material quantities common to all field specimens

Material	Quantity (lb.)
Coarse Aggregate	305
Fine Aggregate	196
Cement	124

3.5 AMBT Overview

The AMBT is a relatively quick way to assess whether or not an aggregate will exhibit deleterious expansions due to ASR. The test is completed in 16 days from initial castings, and expansions are commonly measured through 28 days of exposure. It prescribes the proportion of cement to aggregate, as well as the aggregate sizes for the mortar with a water-to-cement ratio of 0.47. Materials are used to cast three 1 x 1 x 11.25 in. (25 x 25 x 285 mm) mortar bars; this is considered one set. Each bar has a steel gauge stud on the ends to measure expansions with a length comparator. Fine aggregate is washed to remove adhered extra fine particles and provide consistency among materials sent to other laboratories. Some investigators have been concerned that prolonged RCA washing might alter the characteristics of the RCA by eroding away adhered mortar, hydrating dehydrated cement particles in the RCA, or washing away calcium hydroxide, alkalis (Shehata et al. 2010), or existing ASR gel within the RCA. However, work done by Shehata determined there was no significant change in expansion when an 18-hour washing method was used (Shehata et al. 2010). When washing RCA, clear runoff is hard to obtain with RCA, therefore, the fine aggregate was washed using a prescribed time method as follows:

- Sieve #8 = three and a half minutes
- Sieve #16 = five minutes
- Sieve #30 = six minutes
- Sieve #50 = seven minutes
- Sieve #100 = eight minutes

Within Adams et al., 2013, a modified mixing procedure was suggested to eliminate early expansions due to an increased absorptivity exhibited by RCA. For this study, the standard mixing procedure in ASTM C305 was used. Once the bars are cast they are stored in a moist room for 24 ± 2hrs then demolded and placed in a container full of water at room temperature. The specimens are then placed in an oven at 176±3.6°F (80°C ± 2.0°C) for 24 ± 2hrs. The mortar bars are then measured as day zero and placed in a 1 N NaOH solution that is already at 176±36°F (80°C ± 2.0°C). The bars are measured periodically throughout a 14-day period from day zero. For this study, the measurements were extended to 28 days. Expansions below 0.1% are considered innocuous and expansions larger than 0.2% are indicative of potentially deleterious expansions. Expansions between 0.1% and 0.2% include aggregate that may have innocuous or deleterious expansions in field performance (ASTM C1260). An important note on the AMBT is that the expansion limits and precision limits were set for natural aggregates, and may not be applicable for RCA (Rogers 1999). This is further propagated by Adams et al., 2015, as RCA was discovered to "significantly reduce the risk of cracking when incorporated in a high cracking risk mixture." While this conclusion was deduced from a battery of shrinkage tests, it leads the idea that concrete incorporating RCA may be able to undergo more strain before cracking. With this in mind, the current limits may be conservative when predicting whether an aggregate's reactivity is deleterious or not.

3.6 CPT Overview

The CPT as defined by ASTM C1293 is carried out over one year for normal concrete specimens and two years for concrete specimens containing supplementary cementitious materials. The benefit of this test over the AMBT is that it “tests a larger specimen, uses a full scale concrete mixture, and the testing environment is far less harsh that the AMBT” (Ideker et al. 2012b). In addition, the test does not subject the specimens to such an intense environment, allowing for expansions that better replicate field results. The test uses four 3 x 3 x 11.25 in. (75 x 75 x 285 mm) prisms with a water-to-cement ratio between 0.42 and 0.45. One set is considered four specimens. A specific proportion of coarse aggregate and cement content is used in conjunction with the absolute volume method described by the Portland Cement Association (Kosmatka et al. 2003). The cement is required to have a base total alkali content of 0.9±0.1% Na_2O equivalent, which is boosted to 1.25% by mass of cement through the addition of NaOH. The specimens themselves have a steel gage pin on each end for measuring the expansion with a comparator and are stored at 100% relative humidity in an oven at 100°F (38°C). A relative humidity of 100% is achieved by suspending the specimens in a five-gallon bucket over approximately one inch of water. A wicking fabric is used to line the inside of the bucket to help maintain the desired humidity constant. A screw top lid is used to seal the bucket and trap the moisture, allowing for the humidity to build when the buckets are stored in the oven. The expansion limit for the CPT is 0.04% at one year for potentially deleteriously reactive aggregate.

4. DETAILED STUDY ON WYOMING AGGREGATES

All eight aggregate sources in Wyoming were tested using field specimens, AMBT and CPT methods; results of this work are presented within sections 0, 0, and 4.3, respectively, for Black Rock and Knife River. The other six Wyoming aggregates for AMBT and CPT are listed in the appendix along with a tabularized summary of the results.

4.1 Field Specimens

Named after the source pit by which they were cast, the aggregate within the field specimens in Figure 4.1 and Figure 4.2 come from the eight Wyoming pits specified in section 03.1. The aggregate within the field specimens in Figure 4.3 come from demolished Wyoming structures made into RCA-S and RCA-OPP (designated in the figure as STEP and OPP, respectively). These field blocks were last measured between May and June of 2015. Most of them are nearing the seven-year-old mark for field exposure; Labarge is younger at only five-and-a-half-years old, and the RCA field specimens RCA-S and RCA-OPP are younger still at approximately four years old. RCA-S is the aggregate in the field specimens designated STEP. Each graph shows expansion on the vertical axis and time in months on the horizontal axis. The un-boosted designation indicates that the specimens did not receive additional alkalis during casting; boosted specimens received additional NaOH to reach a 1.25% total alkali content. As expected, the boosted specimens show much larger expansion levels. Figure 4.1 through Figure 4.3 demonstrate an overview of each aggregate source and its relationship with reactivity thresholds. These thresholds, tabulated in Table 4.5, are indicated by diagonal lines and were determined by the UW research team (Kimble et al. 2015). For simplicity, the limits for boosted specimens are double that of un-boosted specimens. Figure 4.1 shows un-boosted field specimens and Figure 4.2 shows boosted field specimens.

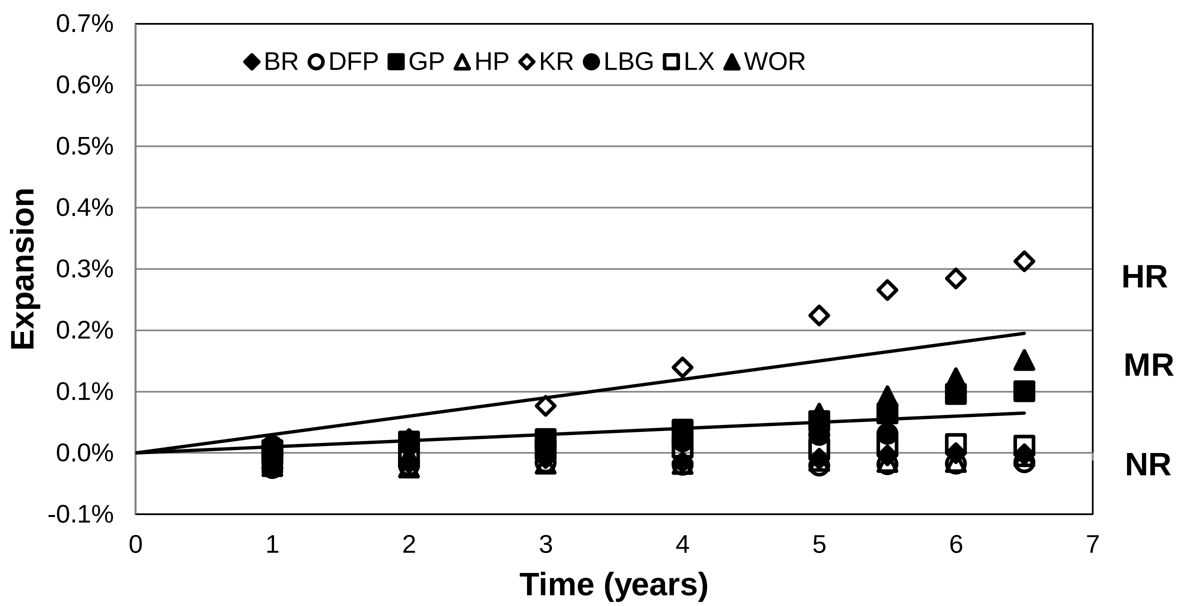


Figure 4.1 Overview of un-boosted field specimen expansions.

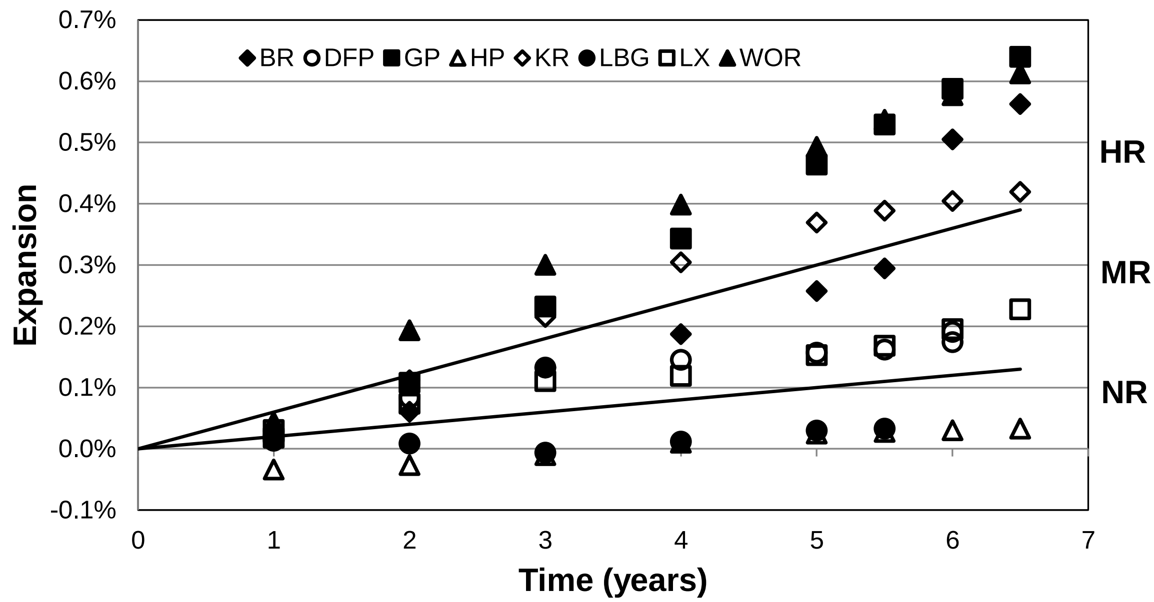


Figure 4.2 Overview of boosted field specimen expansions.

The discontinuity in the boosted specimen for Black Rock is because one of the least reactive blocks was used in an RCA AMBT interlaboratory study. Upon removal of this specimen, the average of the other three blocks raised the reactivity designation from MR to HR.

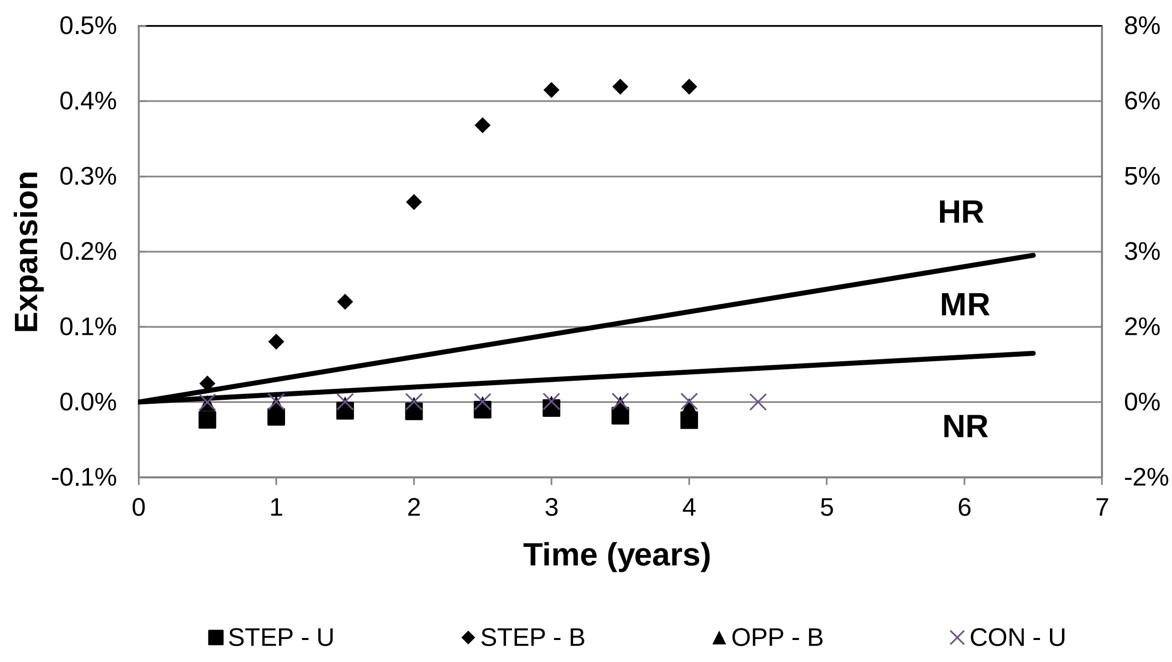


Figure 4.3 RCA field specimen expansions. Note: right axis applies to boosted steps because of the larger expansions. U = Un-boosted, B = Boosted.

4.2 AMBT Natural Aggregates (coarse and fine combined)

UW researcher Hacker performed the AMBT on the eight aggregate sources in three combinations, while Fertig only performed the test on mixed coarse and fine aggregate. The three aggregate combinations are natural fines, crushed coarse, and a combination of 60% crushed coarse and 40% fine. Figure 4.4 and Figure 4.5 illustrate AMBT results from the natural Black Rock and Knife River aggregates.

A summary of classifications based on the Federal Highway Administration (FHWA) limits is shown in Table 4.1. In the figures, dashed horizontal lines represent the 0.10% expansion limit separating nonreactive and moderately reactive aggregates, the 0.30% limit distinguishing moderately reactive and highly reactive aggregates, and the 0.45% expansion limits characterizing the boundary between highly reactive and very highly reactive aggregates (Thomas et al. 2012). The vertical dashed line shows the classification day.

Table 4.1 FHWA classification limits for AMBT

Aggregate-Reactivity Class	Description of Aggregate Reactivity	14-Day Expansion in AMBT (%)
R0	Non-reactive (NR)	≤ 0.10
R1	Moderately reactive (MR)	> 0.10, ≤ 0.30
R2	Highly reactive (HR)	> 0.30, ≤ 0.45
R3	Very highly reactive (VHR)	> 0.45

Table 4.2 is snapshot of the summary of the average expansions for both Black Rock and Knife River in Table A.2 on day 14.

Table 4.2 Natural aggregate AMBT average expansions.

Source	$\bar{x}$
BR	0.598%
KR	0.248%

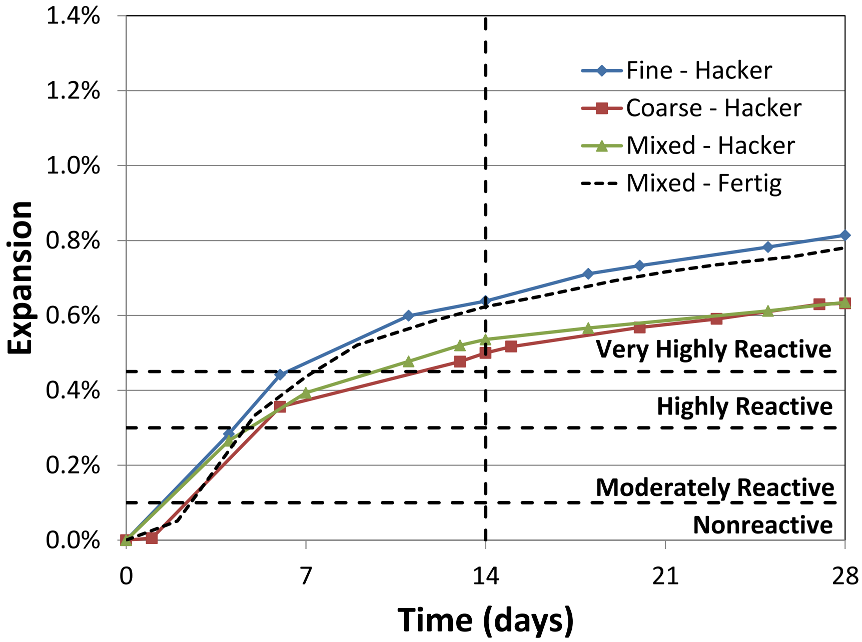


Figure 4.4 AMBT results for Black Rock

The Black Rock AMBT suggests that the aggregate is very highly reactive, being above 0.45%, while the CPT in Figure 4.6 and Figure 4.7 suggests that the aggregate is only moderately reactive. This is summarized in section 0.

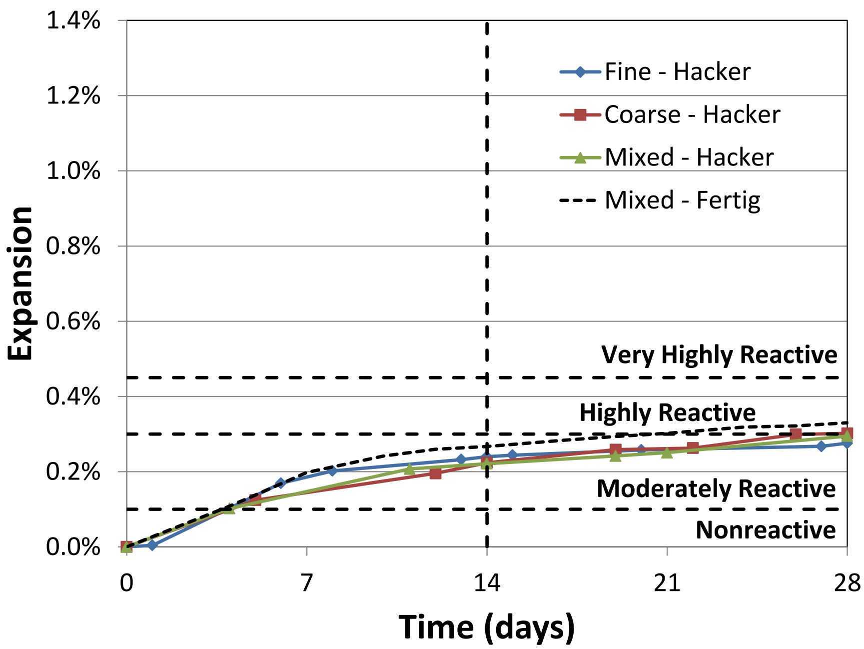


Figure 4.5 AMBT results for Knife River.

Knife River AMBT expansions suggest that the aggregate is moderately reactive, while the CPT suggests that the aggregate is highly reactive being above the 0.12% limit. These data suggest that the most commonly performed test is not in agreement with a more rigorous test. These data are concerning, particularly when combined with the poor field performance of Knife River aggregate within the state of Wyoming.

4.3 CPT Test Results

A complete set of CPTs was performed by Fertig (Fertig et al. 2013). Figure 4.6 demonstrates the CPT expansions as a function of time for both natural Black Rock and natural Knife River aggregates. A summary of classifications based on FHWA limits is shown in Table 4.3.

Table 4.3 FHWA classification limits for CPT

Aggregate-Reactivity Class	Description of Aggregate Reactivity	One-Year Expansion in CPT (%)
R0	Non-reactive (NR)	≤ 0.04
R1	Moderately reactive (MR)	> 0.04, ≤ 0.12
R2	Highly reactive (HR)	> 0.12, ≤ 0.24
R3	Very highly reactive (VHR)	> 0.24

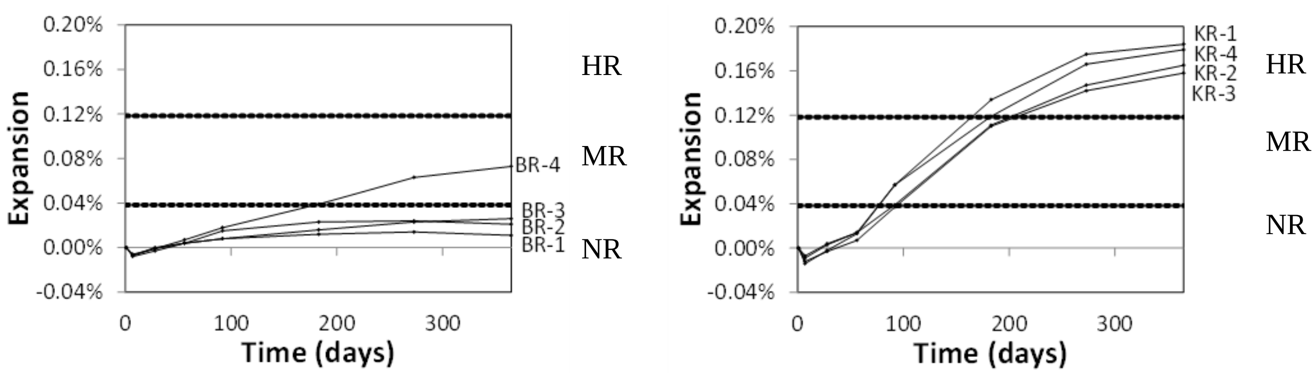


Figure 4.6 A and B CPT results on natural Black Rock and Knife River aggregate, respectively.

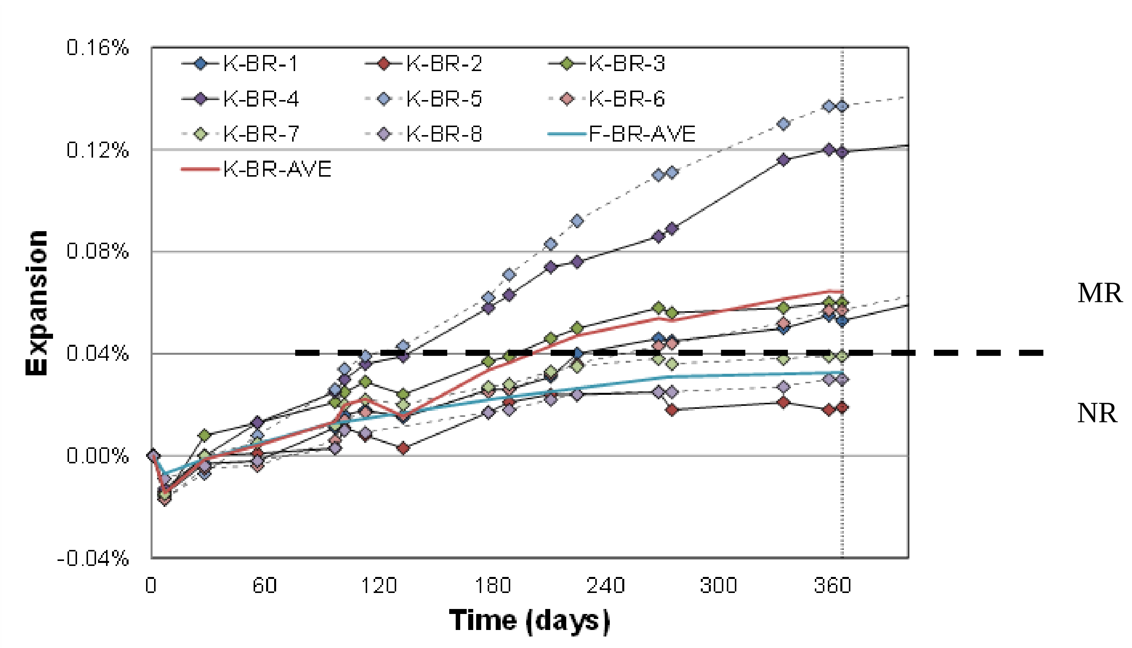


Figure 4.7 Additional CPT results on natural Black Rock aggregate. Note: F and K represent the operator that cast the specimen, F=Fertig and K=Kimble.

Based on the perceived outlier for Black Rock, an additional two sets, or eight more CPTs on natural Black Rock aggregate, were cast. Their expansions are presented in Figure 4.7. In each set of four specimens, one specimen exceeded the 0.04% limit that ASTM 1293 designates as potentially deleteriously reactive. As a result of the additional testing, the one expansion reading is valid and is attributed to non-uniformity in the aggregate as received. The average of all specimens falls below the limit for reactive aggregate. A further breakdown is found in Table A.2 for each of the eight aggregate sources.

4.4 Classification System

Classifications are primarily based on the CPT and field specimens. AMBT test results from Hacker and Fertig were then used in conjunction with the CPT classification from the FHWA displayed in Table 4.3 and the field specimen classifications to produce the final classification of the aggregate denoted in Table 4.4. Due to the rarity of field exposure blocks and consolidated classification methods, a preliminary classification system for the field blocks has been developed and is presented in Table 4.5 (Kimble et al. 2015).

Table 4.4 Aggregate classifications

Source	Classification by Test				Final Classification
	Field Exposure Unboosted	Field Exposure Boosted	CPT	AMBT	
BR	NR	MR	MR	VHR	Moderately Reactive
DF	NR	MR	NR	VHR	Nonreactive
GP	MR	HR	MR	VHR	Moderately/Highly Reactive
HP	NR	NR	NR	MR	Nonreactive
KR	HR	HR	HR	MR	Highly Reactive
LBG	NR	NR	HR	MR	Potentially Reactive
LX	NR	MR	MR	VHR	Moderately Reactive
WOR	MR	HR	MR	VHR	Moderately Reactive

Based on the FWHA limits, the Black Rock AMBT indicates that the aggregate is very highly reactive; however, results from the CPT and boosted field specimens denote that the aggregate is moderately reactive. It has been previously studied that the AMBT and CPT sometimes indicate conflicting reactivity levels (Lu et al. 2004; Thomas et al. 2006; Ideker et al. 2012b). Additionally, Ideker et al., 2012b, has shown that the CPT has a much better correlation with field performance than the AMBT. In fact, according to the article there are no reported cases of deleterious expansion in field concretes containing aggregates that have passed the CPT. Because of these reasons, Black Rock aggregate is designated as moderately reactive (Kimble et al. 2015).

Table 4.5 UW field exposure block classification

Classification	Limit (percent expansion/year)	
	Un-boosted	Boosted
NR	<0.01	<0.02
MR	0.01<x<0.03	0.02<x<0.06
HR	>0.03	>0.06

5. RCA EVALUATION

Each of the AMBTs using RCA within this study were performed using two different percentages of RCA. These levels are 20% RCA and 50% RCA. Thus the mortar bars for the first level comprised 20% RCA and 80% nonreactive. The second level mortar bars consisted of 50% of each constituent. In order to differentiate these, the designation RCA-20X indicates that the test results are for the first level of 20% RCA for the specific aggregate X. For example, RCA-20BR indicates that the test was performed using RCA with Black Rock aggregate at 20% RCA with the remaining 80% nonreactive aggregate. This nomenclature is also repeated in Table 3.2.

5.1 Recycled Concrete Aggregate

Data from the interlaboratory studies (RCA-S, RCA-KR, and RCA-BR) are presented in this section. The line graphs illustrate expansions as a function of time and display the overall spread among all laboratories, with the dark dashed line being the overall average. The legend indicates the laboratory number and the casting done. Thus a designation of 1-1 indicates laboratory 1 and casting 1. The bar graphs give a sense of the overall trend of expansions between the laboratories and castings. The dark bars indicate the first casting and the grey hashed bars indicate the second casting for the indicated material. Table 5.1 indicates what sets of tests were performed by each laboratory. In general, one casting consists of three mortar bars. RCA-S had a total of nine participating laboratories to meet the minimum of six defined in ASTM E691. RCA-BR and RCA-KR had a total of 10 laboratories according to ASTM C670. A more detailed discussion can be found in section0.

Table 5.1 RCA AMBT laboratory testing.

laboratory	RCA-S		RCA-BR and RCA-KR	
	Casting 1	Casting 2	Casting 1	Casting 2
1	X	X	X	X
2	X	X	X	X
3	X	X	X	X
4	X	X	X	X
5	X	X	X	
6	X	X	X	X
7	X	X		
8	X	X	X	
9	X		X	
10			X	X
11			X	

Note: laboratory 11 is also laboratory 3 but tests were completed by a different operator.

5.1.1 RCA-S

Individual expansions for RCA-S are presented in Figure 5.1 through Figure 5.4.

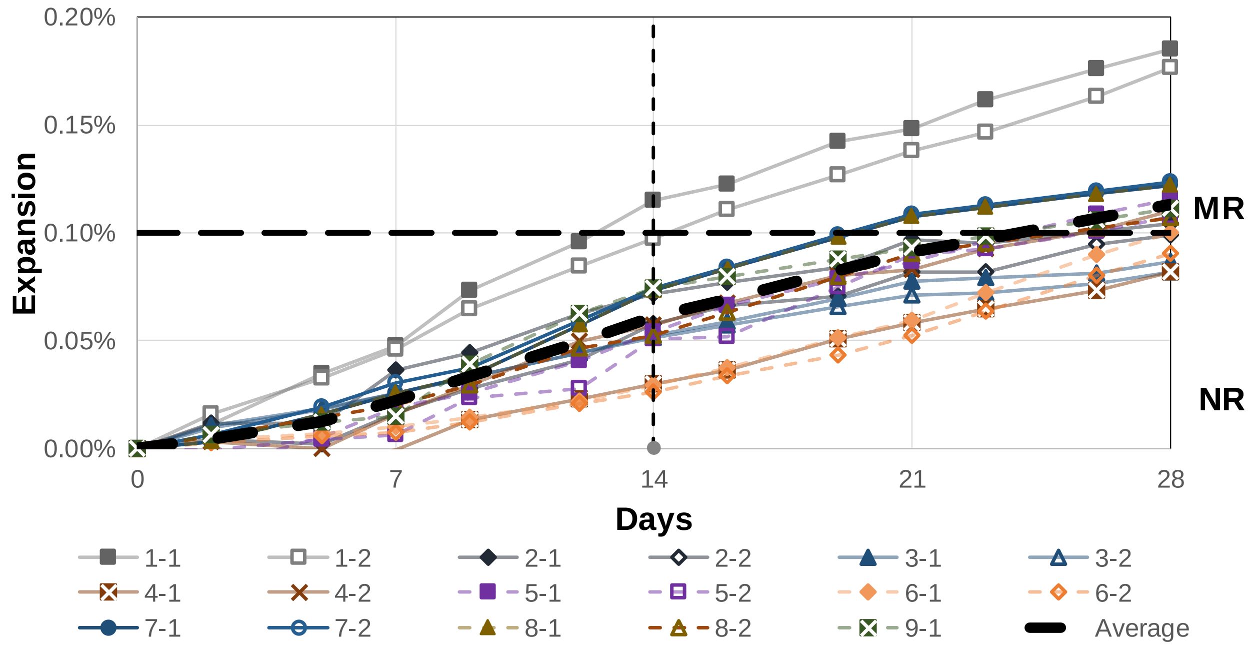


Figure 5.1 AMBT test results for RCA-20S.

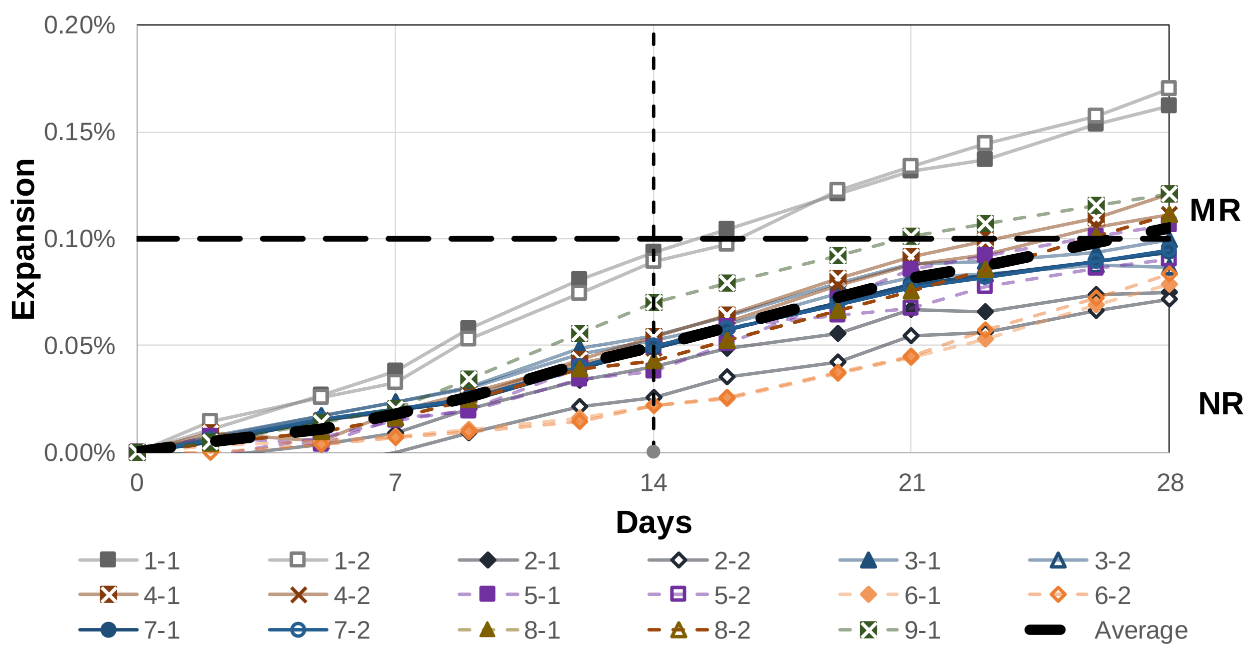


Figure 5.2 AMBT test results for RCA-50S.

In Figure 5.3 and Figure 5.4, the order of black bars are: laboratories 1-9. The order of the grey hashed bars are: laboratories 1-8.

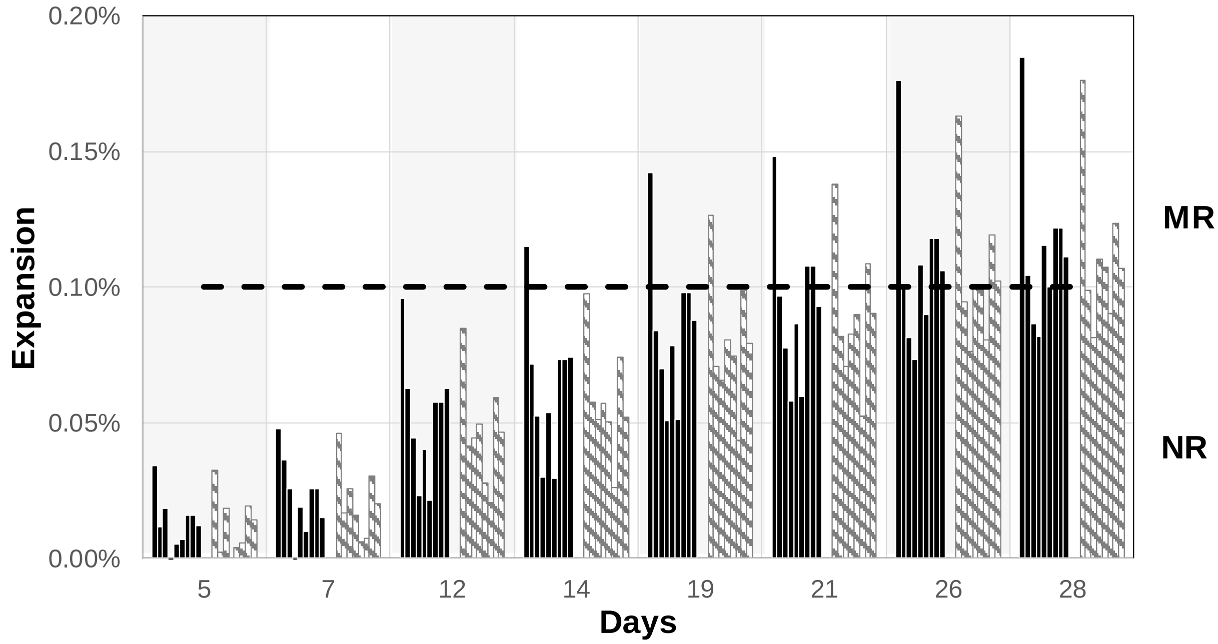


Figure 5.3 AMBT test results for RCA-20S.

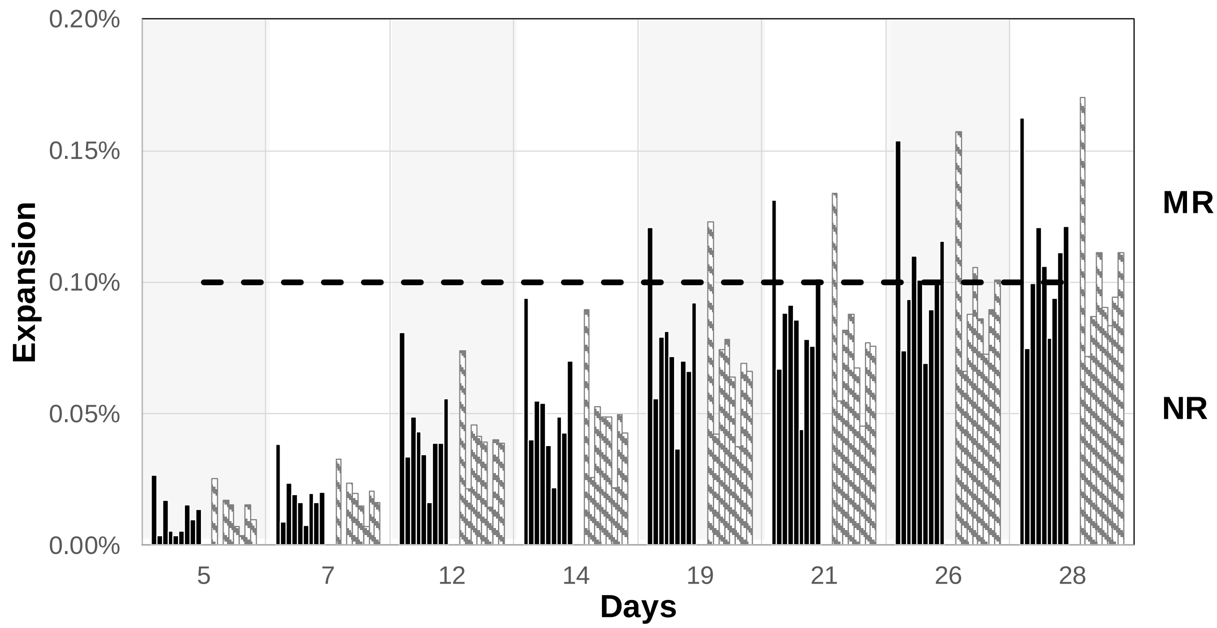


Figure 5. Error! No text of specified style in document.**4** AMBT test results for RCA-50S.

The compiled data for RCA-S indicates that the expansions from the AMBT were independent of the percentage of RCA used. Unfortunately, it is not known what aggregates were used in the parent concrete of RCA-S and RCA-OPP to provide a comparison between the aggregate and its corresponding RCA. However, the original concrete steps did exhibit severe ASR damage, which is indicative of a highly reactive aggregate. The field specimen Steps-B in Figure 4.3 corroborates this by indicating approximately 6% expansion, which surpasses the highly reactive threshold. It is worth noting that the threshold for potentially deleterious expansions in AMBT is 0.1% at 14 days and that the average of RCA-20S and RCA-50S is 0.052% and 0.048%, respectively, and 0.101% and 0.104%, respectively, at 28 days. According to the FHWA, limits outlined in Thomas et al. 2012 such expansions place RCA-S as moderately reactive at 28 days. However, ASTM C1260 indicates that innocuous behavior occurs in expansions at 14 days of less than 0.1% in most specimens, placing RCA-S as NR for both levels of 20% and 50% of RCA.

5.1.2 RCA-BR

Expansion results for RCA-BR are presented in Figure 5.5 through Figure 5.8.

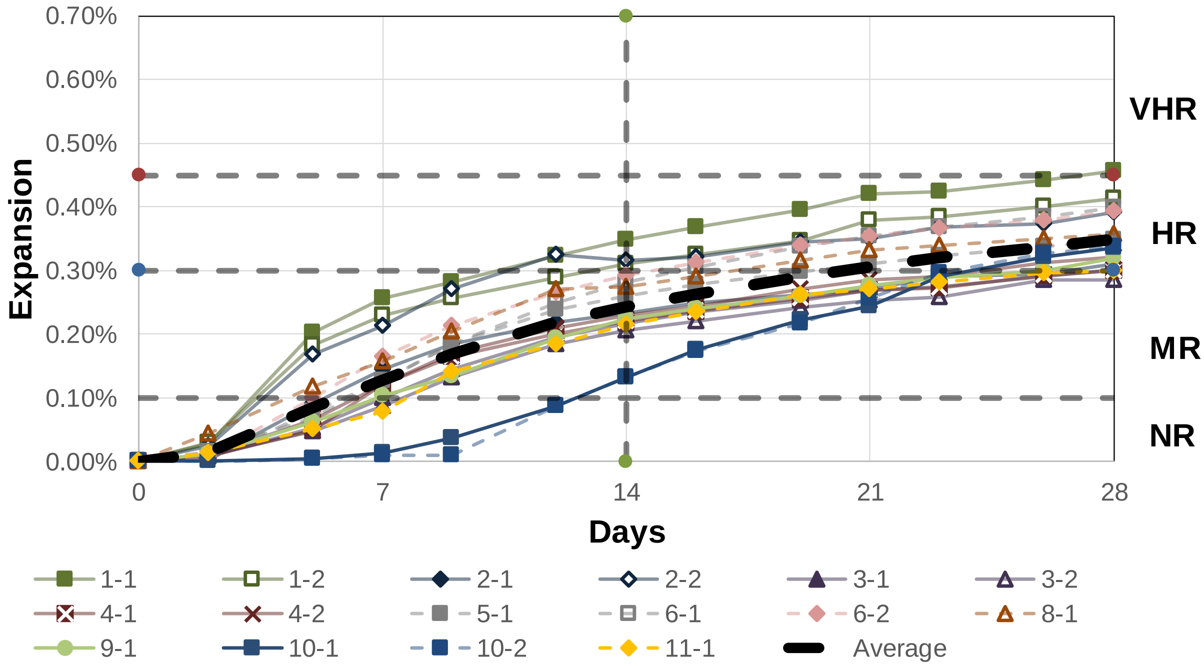


Figure 5.5 AMBT test results for RCA-20BR.

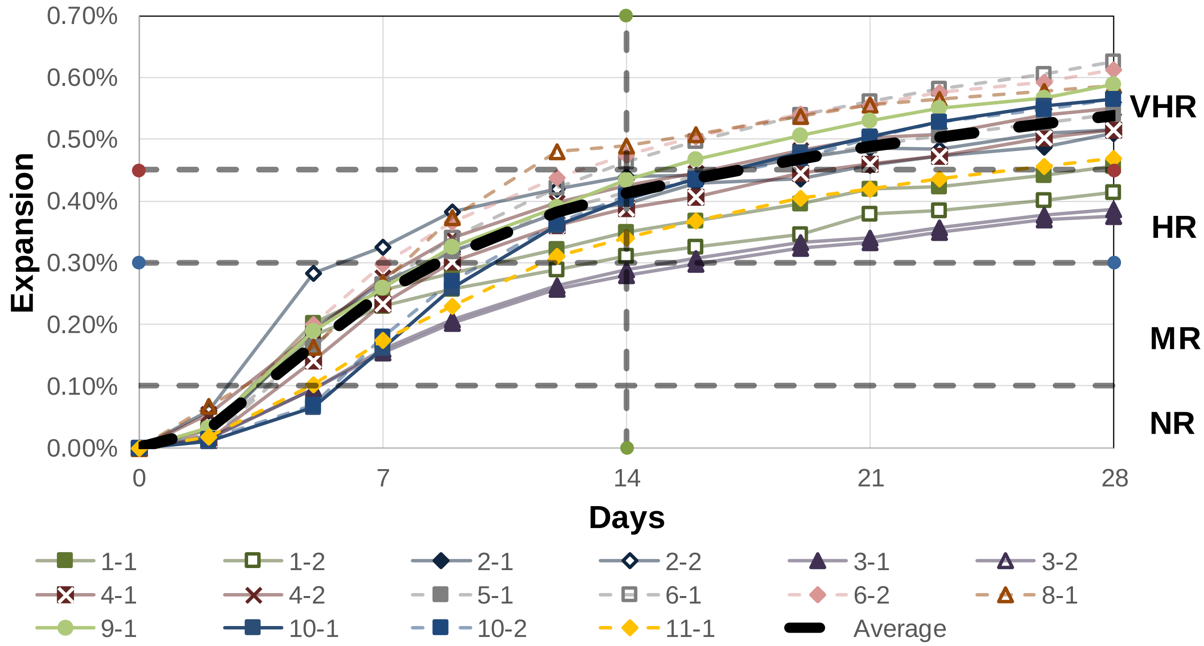


Figure 5.6 AMBT test results for RCA-50BR.

In Figure 5.7 and Figure 5.8, the order of black bars are laboratories 1-11 with the exception of 7. The order of the grey hashed bars are Laboratory 1-4, 6 and 10. There are fewer grey bars because not all laboratories performed two castings.

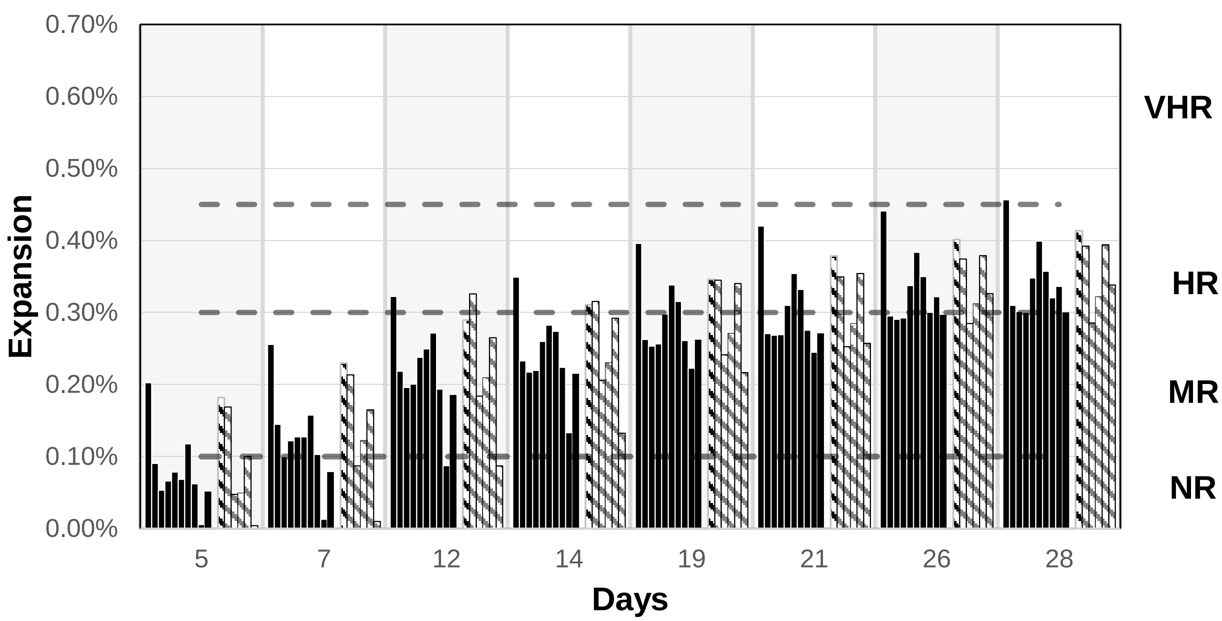


Figure 5.7 AMBT test results for RCA-20BR.

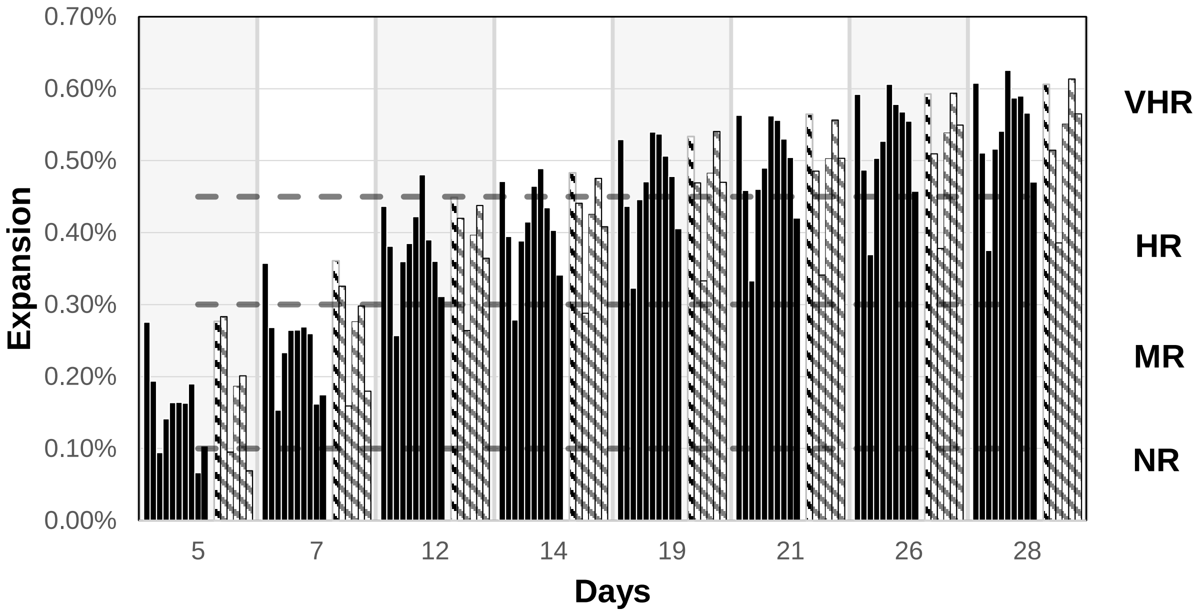


Figure 5.8 AMBT test results for RCA-50BR.

The compiled data for RCA Black Rock AMBTs indicate that RCA-50BR has larger expansions than those from RCA-20BR. This indicates that the expansion from the AMBT may correlate to the amount of RCA containing Black Rock aggregate. Additionally, the expansions from both 50% and 20% AMBT are less severe than the test results from the natural Black Rock aggregate. The natural aggregate exhibited an average expansion of 0.598%, while the Black Rock RCA had an average expansion of 0.243% and 0.414% for 20BR and 50BR, respectively. Because the AMBT with natural aggregate utilized 100% Black Rock, a direct comparison is difficult to deduce due to the possible correlation between expansion and quantity of RCA-BR used. Fortunately, a study done by Li and Gress 2006 discovered that 100% RCA mortar bars exhibit lower levels of reactivity than their natural aggregate.

5.1.3 RCA-KR

Expansion results for RCA-BR are presented in Figure 5.9 through Figure 5.12.

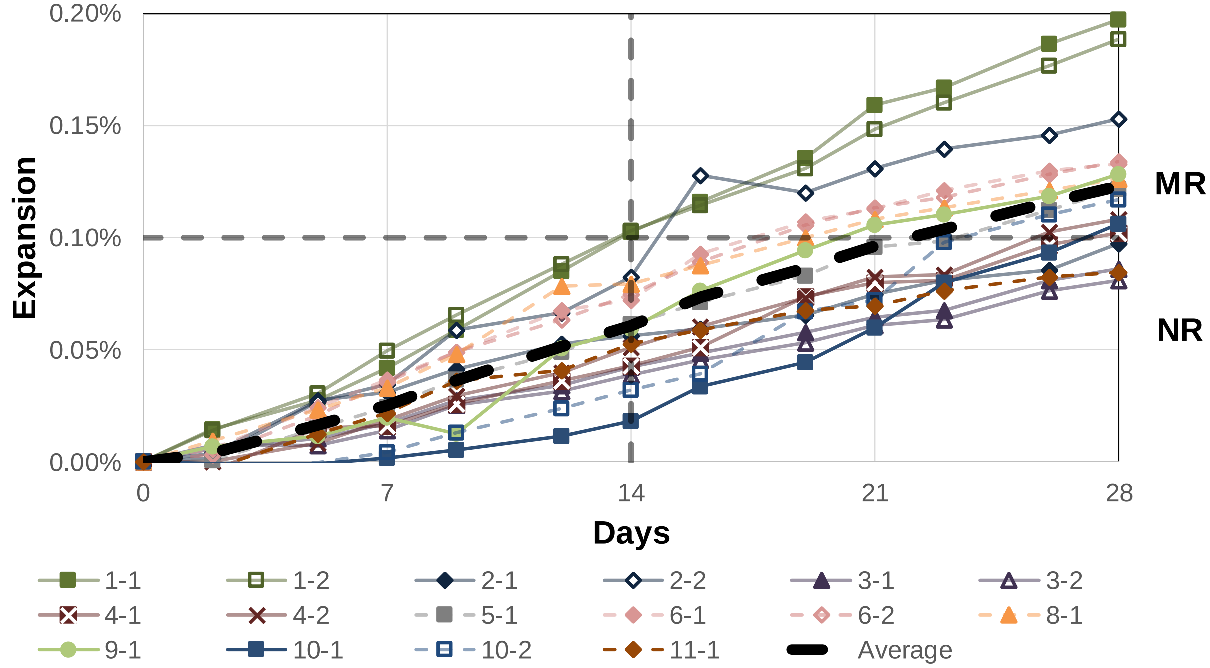


Figure 5.9 AMBT test results for RCA 20KR.

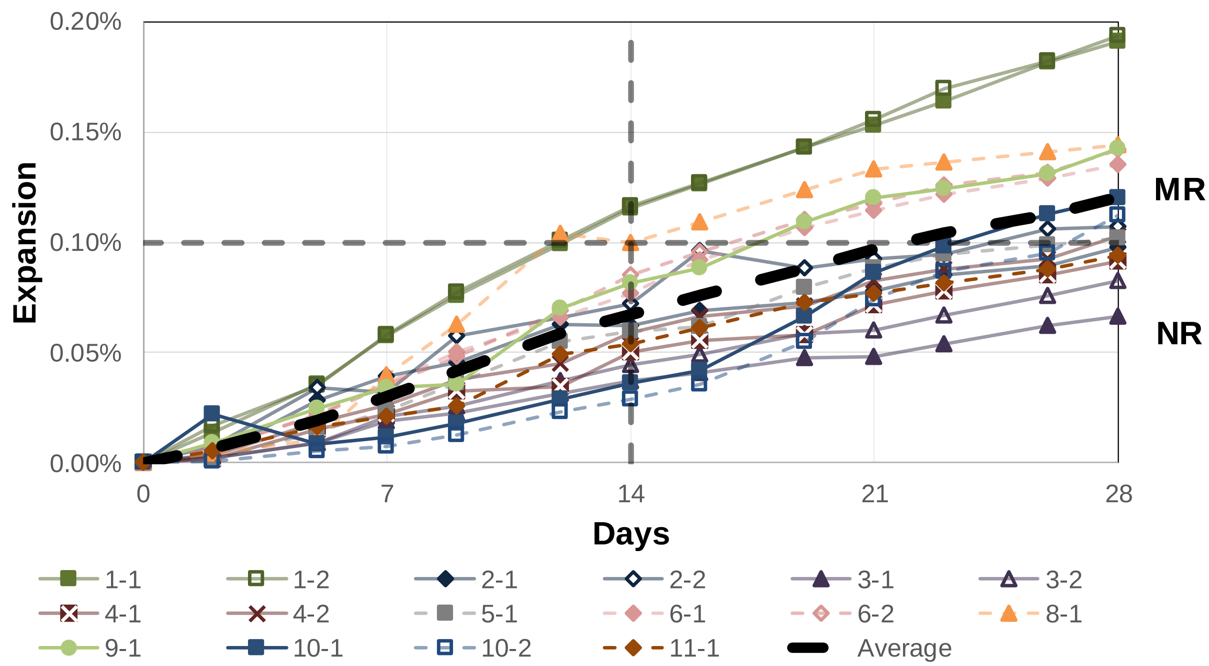


Figure 5.10 AMBT test results for RCA 50KR.

In Figure 5.11 and Figure 5.12, the order of black bars are Laboratories 1-11 with the exception of 7. The order of the grey hashed bars are Laboratory 1-4, 6 and 10. There are fewer grey bars because not all laboratories performed two castings.

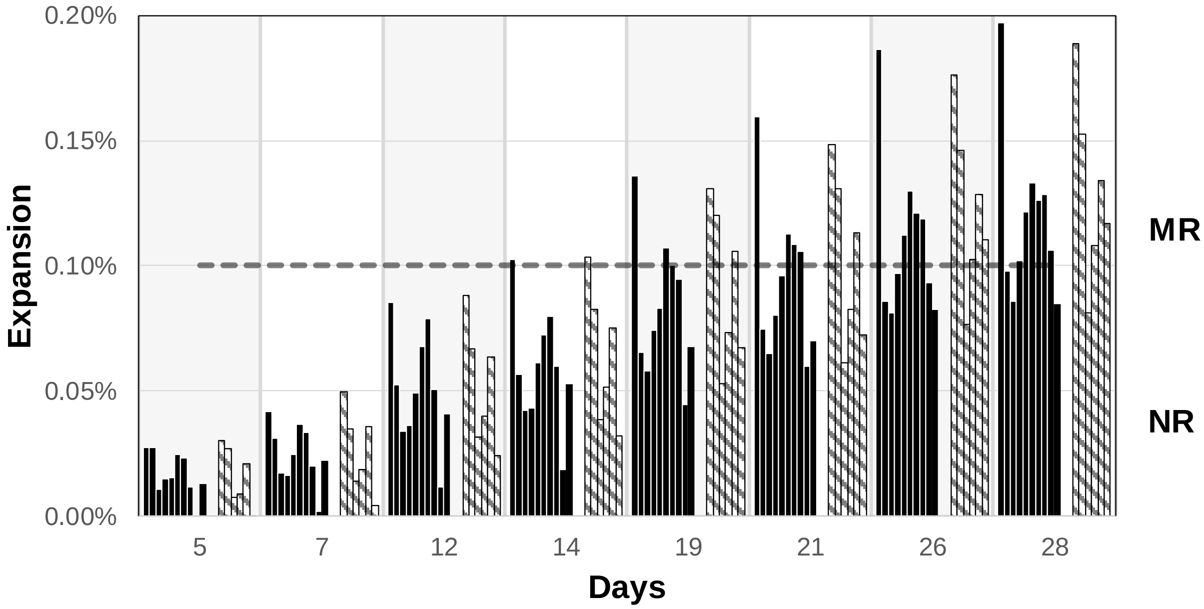


Figure 5.11 AMBT test results for RCA 20KR.

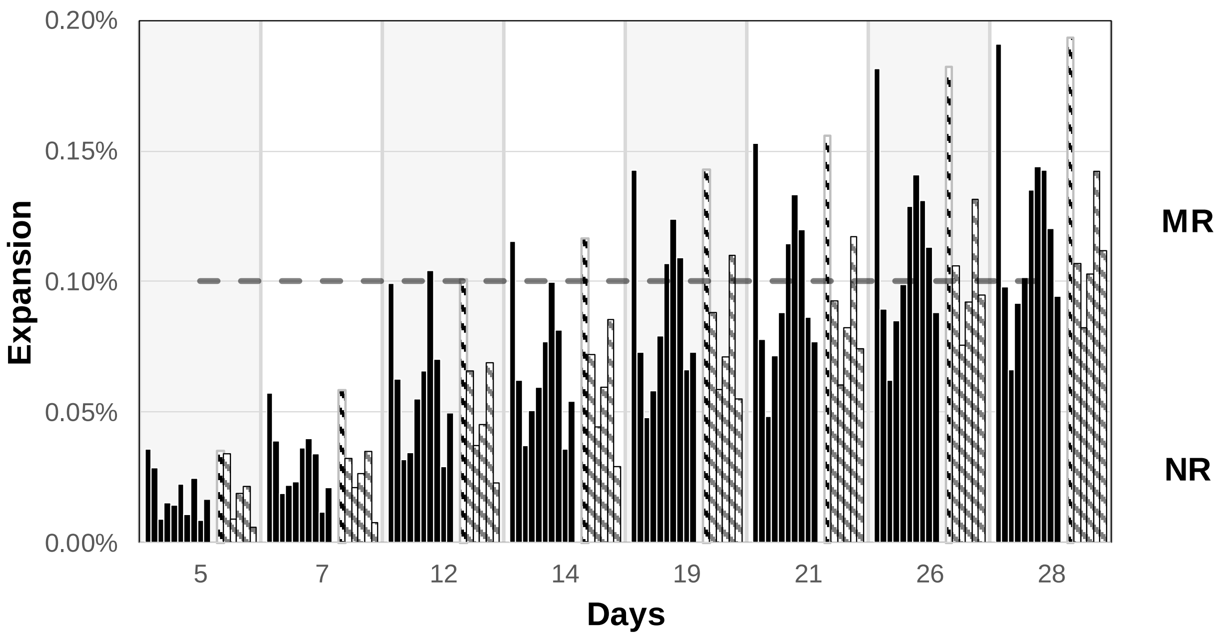


Figure 5.12 AMBT test results for RCA 50KR.

The compiled data for the RCA-KR produced consistent behavior with RCA-S and an opposing trend from RCA-BR because the two levels of RCA did not appear to affect the expansions from the AMBT. In fact the average expansions for RCA-20KR and RCA-50KR were 0.06218% and 0.0687% with a standard deviations of 0.02192 and 0.02602%, respectively. Because the expansions for KR appear to be independent of the level of RCA within the specimens, the natural aggregate AMBT can be compared directly with more confidence. Both of the averages here are lower than the expansions achieved with the natural aggregate of 0.248%.

5.1.4 RCA Discussion

Although RCA-BR and RCA-KR did not produce the same behavior with varying levels of nonreactive aggregate, this study shows that the AMBT is sensitive to characteristics inherited by the natural aggregate in the parent concrete. It takes very few reactive minerals to produce deleterious ASR, varying from as little as 0.5% to 5% by mass (Farny et al. 1997). Additionally, ASR behaves in a way known as the pessimum effect (Stanton 1940, Ichikawa 2009). This means there is a certain level of reactants and particle size that creates a deleteriously expansive environment for ASR. This is somewhat analogous to the concept of a resonant frequency in structural dynamics. Therefore, there may be the right amount of reactive constituents to create that maximum reaction within both levels of RCA-KR, or both levels of RCA miss the maximum and just happen to have the same level of reactivity. RCA-BR, however, seems to be approaching that peak level with increasing levels of RCA. Because RCA also contains a cement paste, the amount of aggregate or exposed aggregate to ASR can be highly variable. Each batch of AMBTs would therefore have differing levels of reactivity as a function of the amount of adhered mortar present in each batch. While the results of these studies seem to indicate it is more common to see behavior in ASR independent of the proportion of RCA used, the experiments documented in Adams et al., 2013, the pessimum effect and the expansions observed in RCA-BR suggest it is more common to see ASR expansion correlated to the proportion of RCA used. Figure 5.13 is an example of the pessimum effect seen in a chart from Stanton 1940 where expansion is plotted against the percentage of reactive limestone.

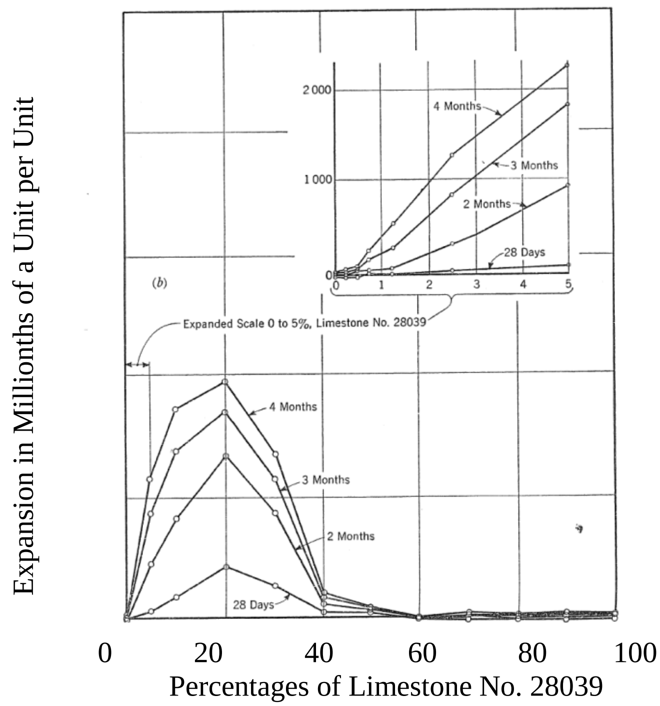
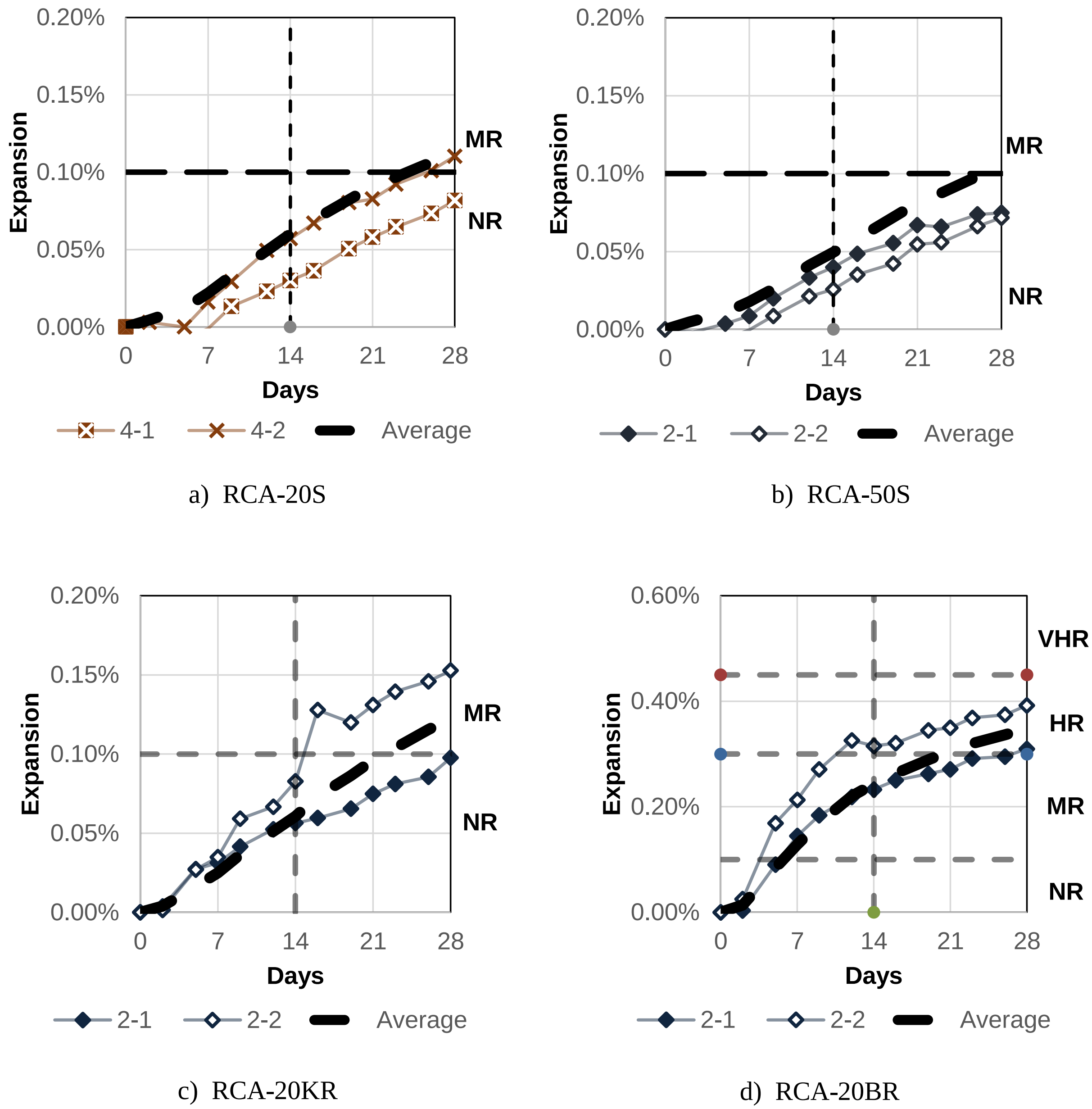


Figure 5.13 Pessimum effect (Stanton 1940).

Figure 5.14 a-d presents a closer look at Laboratory 2 results for RCA-20BR and RCA-20KR and Laboratory 4 results for RCA-20S; here it can be seen there is a noticeable split in the data. The bold dashed line indicates the average of all participating laboratories for their respective material. These figures display the most significant differences between castings of the same material within the same laboratory. While it is not certain why these differences occurred, these are reflected in the following section on precision. It is also worth noting that while visibly large splits are an indicator, small variations can become large if the variations from all the other laboratories are smaller.



a) RCA-20S

b) RCA-50S

c) RCA-20KR

d) RCA-20BR

Figure 5.14 Differences in measured expansions for a single laboratory a-d.

5.2 Precision Analysis

Consistency statistics are performed in order to analyze and identify any data that do not statistically fit with all the other data. Additionally, these statistics give an overall feel for the variability of the test method. ASTM E691 defines variables k and h to evaluate sets of data in interlaboratory studies.

5.2.1 Consistency Statistics

In this section, values for h and k are presented and discussed based on ASTM E691. For an interlaboratory study, these are performed in two manners: between laboratories (h) and within laboratories (k). The between laboratories statistic illustrates how each laboratory's average compares to the overall averages of all participating laboratories. On the other hand, the within laboratory k statistic shows how a "laboratory's variability on a particular material compares with all the laboratories combined. A value of k larger than one indicates greater within laboratory variability than the average for all laboratories" (ASTM E691). In other words, a k value of one indicates that the laboratory is as consistent in performing a duplicate test as the average consistency of all the participating laboratories. Physically, the k statistic is the standard deviation of the laboratory in question divided by standard deviation of all the participating laboratories' average expansions. The k limit line may also indicate within laboratory imprecision. The h statistic will vary based on the number of laboratories that performed the test. The k statistic depends on both the number of laboratories and the number of replicate tests. Figure 5.15 and Figure 5.16 show the consistency statistics between laboratories (h) and within each laboratory (k), respectively. Values in Figure 5.15 that are above zero indicate that that particular laboratories' expansions were higher than the average expansion of all the participating laboratories. Likewise, negative h values indicate that particular laboratory's expansions were lower than the average. Additionally, each figure displays critical limit, which is the 0.5% significance level. This means that data from a properly conducted test should reasonably fall below 0.5. The h and k statistic are calculated based on the following equations from ASTM E691.

$$h = d/s_x \qquad \text{Equation 5.1}$$

Where:

d = the laboratory deviation (that is the difference between the laboratory's average expansion and the average of each participating laboratories' average expansion).

s_x = the standard deviation of the average of each participating laboratories' average expansion.

$$k = s/s_r \qquad \text{Equation 5.2}$$

Where:

s = the standard deviation for one laboratory's average expansion.

s_r = the standard deviation of all the participating laboratories' average expansions.

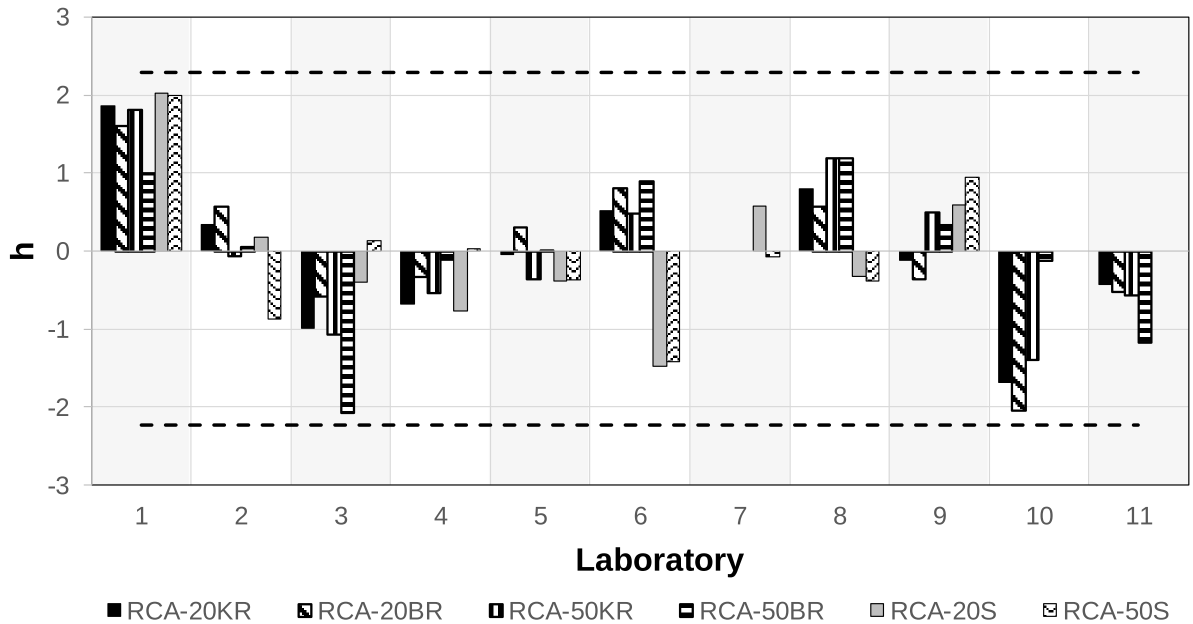


Figure 5.15 Between laboratory consistency statistic *h*. Critical *h* = ± 2.29.

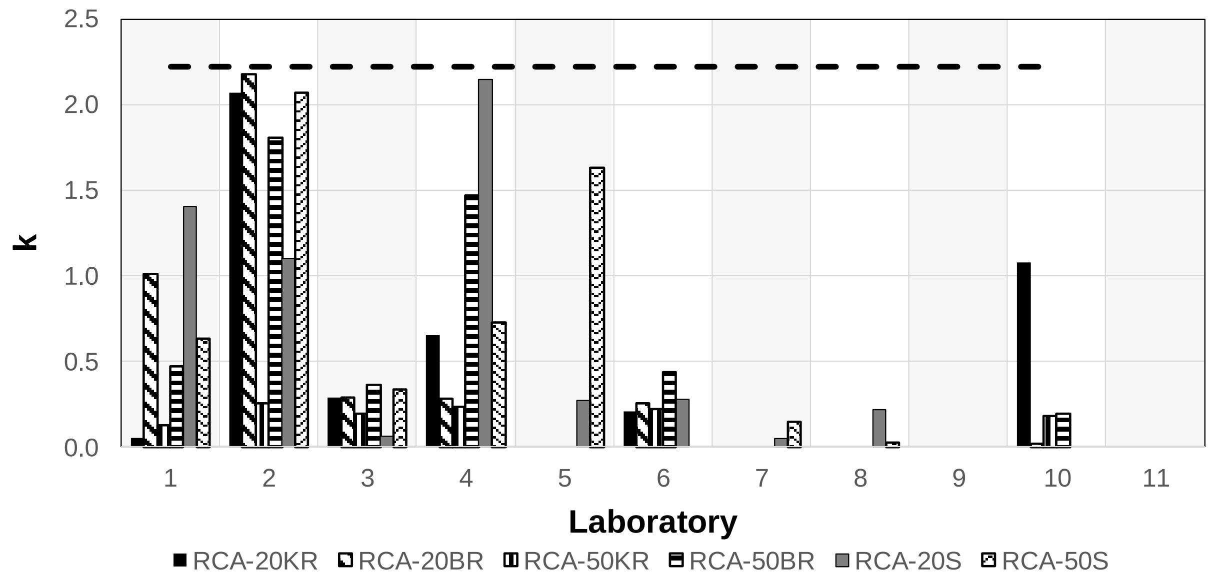


Figure 5.16 Within laboratory consistency statistic *k*. Critical *k* = 2.22.

The critical *h* and *k* lines are used to flag results that need to be investigated. Specifically, a *k* value above the critical limit may indicate laboratory imprecision. These charts indicate that while Laboratory 1 produces high h values, they do not exceed the upper limit. Although Laboratory 1 reports higher expansions than all the other groups, the *h* statistic tells us that based on the number of participating laboratories, Laboratory 1 data are reasonable. Laboratory 3 approaches the limit for one material combination but does not exceed it. Because Laboratory 3 and 10 only have one material combination that exhibits a large difference from the others, it is assumed that the difference is not due to a procedural error. This is confirmed by the within laboratory consistency statistic exhibited in Figure 5.16, which demonstrates that Laboratory 3 is precise within itself by not showing a drastic change for the RCA-50BR material combination. According to Practice E691, the variation between positive and negative *h* values in Figure 5.15 is not a concern because the positive and negative bars are approximately equally distributed. Figure 5.16 raises some questions with Laboratory 2, because the *k* statistic for most of its test results are approaching the *k* limit line. Laboratory 4 also has one test result that approaches the *k* limit line. However, as in the case of Laboratory 1 and the *h* statistic critical line, both of these laboratories are within the expected variability indicated by the limit lines. The *k* statistic is further corroborated by closer examination of each laboratory's day 14 test result. Figure 5.14 a-d highlight the differences between casting one and casting two of the same material within the same lab. While some of these figures do not suggest a large difference, the k statistic is based on standard deviations of all the laboratories day 14 test results. This means that difference is large with respect to how close the other laboratories' test results were. These results are currently under investigation.

5.2.2 Precision Statement

Precision results for each material combination are identified and presented in Table 5.2. Additionally, this table meets ASTM Practice E177. Table 5.2 displays the average, repeatability, and reproducibility standard deviations and their 95% limit in terms of standard deviation and coefficient of variation for each material combination: RCA-20S, RCA-50S, RCA-20KR, RCA-50KR, RCA-20BR, and RCA-50BR. The table is organized by material type.

Table 5.2 Precision for RCA-S, RCA-BR and RCA-KR.

Material	Average expansion	Repeatability standard deviation	Reproducibility standard deviation	Repeatability limit		Reproducibility limit	
	$\bar{x}$ (%)	S_r (%)	S_R (%)	r (%)	CV_r (%)	R (%)	CV_R (%)
RCA-20S	0.061	0.009	0.023	0.025	41	0.065	107
RCA-50S	0.051	0.005	0.021	0.014	27	0.058	114
RCA-20KR	0.062	0.009	0.023	0.025	40	0.064	103
RCA-50KR	0.069	0.005	0.026	0.015	22	0.074	107
RCA-20BR	0.243	0.027	0.057	0.075	31	0.160	66
RCA-50BR	0.414	0.018	0.064	0.050	12	0.180	44

The term's repeatability limit and reproducibility limit are used as defined in ASTM E177. The repeatability limit is the value below which the absolute difference between two individual test results obtained under repeatability conditions may be expected to occur with the probability of approximately 95%. Repeatability conditions mean that independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time. The reproducibility limit is the value below which the absolute difference between two test results obtained under reproducibility conditions may be expected to occur with a probability of approximately 95%. Reproducibility conditions are the conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment.

Table 5.3 quantifies the averages for the AMBT tests on natural aggregates.

Table 5.3 AMBT average expansions for natural aggregates.

Source	$\bar{x}$
BR	0.598%
KR	0.248%

Table 5.4 combines and compares AMBT test results on RCA and ASTM precision statement limits. After identifying the average expansion, the ASTM upper and lower bounds are calculated. This is defined as the values where no two properly conducted tests in different laboratories should differ by more than 43% of the mean expansion (ASTM C1260). The minimum and maximum values are for day 14 test data, and include casting 1 and 2. Table 5.4 then clarifies if experimental results fall within the prescribed limits.

Table 5.4 RCA AMBT results and AMBT precision.

Material	**Average**	**Min**	**Max**
RCA-20S	0.061%	0.026%	0.115%
	Limit	0.035%	0.087%
		Exceeds	**Exceeds**
RCA-50S	0.049%	0.022%	0.094%
	Limit	0.028%	0.071%
		Exceeds	**Exceeds**
RCA-20KR	0.061%	0.018%	0.103%
	Limit	0.035%	0.087%
		Exceeds	**Exceeds**
RCA-50KR	0.243%	0.132%	0.349%
	Limit	0.139%	0.348%
		Exceeds	**Exceeds**
RCA-20BR	0.067%	0.029%	0.116%
	Limit	0.038%	0.096%
		Exceeds	**Exceeds**
RCA-50BR	0.412%	0.279%	0.489%
	Limit	0.235%	0.590%
		Okay	**Okay**

5.3 Discussion of Results

ASTM Practice E691 explains how an interlaboratory study should be performed in order to obtain viable and broadly applicable precision statements. Most notable is that while it is suggested that 30 laboratories are included to adequately profile the population, the absolute minimum number of laboratories for use in a precision statement is six laboratories. ASTM C670 indicates that the requirement for "reliable estimates of precision" are obtained from a properly designed and executed interlaboratory series of tests involving at least 30 degrees of freedom for single operator standard deviation and at least 10 laboratories. E691 further suggests that at least three materials representing different test levels, with six or more being preferable for broadly applicable precision statements be used. For physical tests, three or four replicates are suggested to adequately profile each material. The RCA-S, RCA-BR, and RCA-KR studies presented within this report follow E691 with the exception of including only two replicate tests between material combinations.

Table 5.4 indicates that only one material combination fell within the boundaries set by ASTM C1260. The coefficient of variation (CV) limits from the precision statements for RCA-BR and RCA-KR range from 44% to 107%. While the data suggest that the lower CV limit would be less than the 43% limit designated in the AMBT by fitting within the designated range, the CV is a function of the number of laboratories, the deviation from the average, and the deviation between replicate tests. Because there were only six laboratories that returned replicate test data and a maximum of 11 operators in 10 laboratories, the CV is larger than it would be with more data. Additionally, the AMBT precision statement was developed utilizing 46 laboratories on natural aggregate (Rogers 1999). The RCA AMBT presented within this report showed higher variability than is acceptable by the AMBT. Because each laboratory within this report has experience with the AMBT, the data suggest that RCA exhibits more variability than the natural aggregates. This same trend was also identified in Adams et al., 2013.

It should be noted that the AMBT is difficult because of the very small displacement measurements and different operating styles. While using more laboratories would provide a more robust statistical analysis, the number of laboratories that have experience performing AMBT is limited.

The repeatability and reproducibility limits *r*, *R*, CV_r and CV_R, are currently based on each individual material. Producing a comprehensive limit for all RCA types is ongoing. ASTM C802 describes four types of behavior typical for establishing precision statements. These are: constant standard deviation, constant coefficient of variation, separate groups with constant standard deviation or coefficient of variation, and irregular or nonlinear relationships between standard deviation, coefficient of variation, and average level. Table 5.2 reveals there is not a constant standard deviation for the data. The second type is better viewed in Figure 5.17. This figure plots the repeatability standard deviation (S_r) and the reproducibility standard deviation (S_R) for each material against the average expansion. As a result, the slope of the trend line corresponds to the coefficient of variation. From this figure it can be seen that only the reproducibility coefficient of variation could be considered constant at first glance. ASTM C802 suggests, in the case of irregular or nonlinear relationships, that statistical methods such as Bartlett's test be used to establish whether the variance estimates are statistically similar. Advice of a statistical consultant is encouraged when working with irregular or nonlinear relationships. The authors are looking into this method.

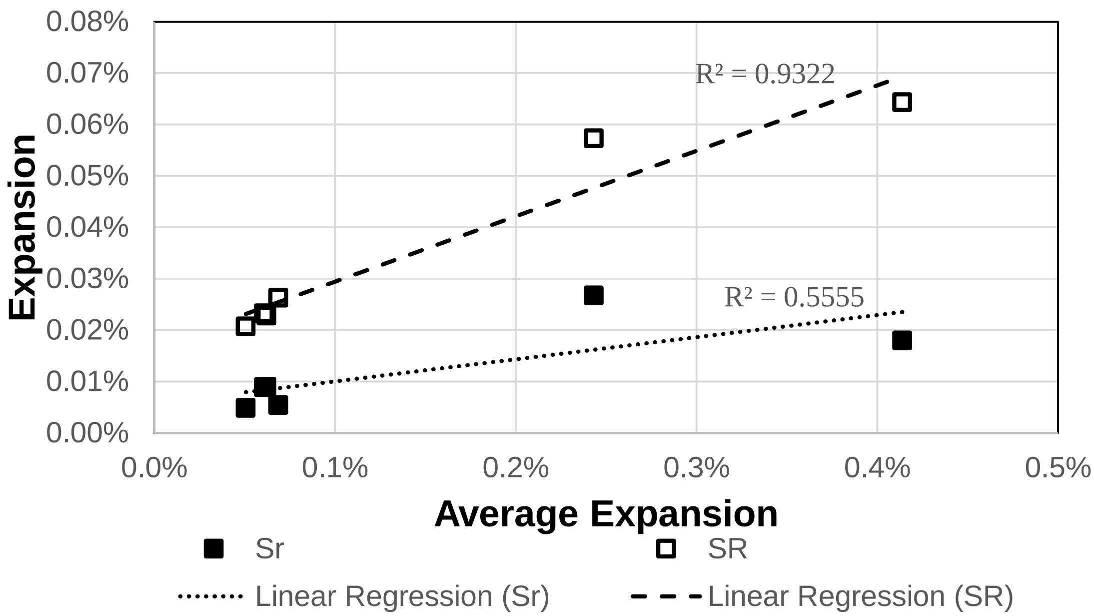


Figure 5.17 Standard deviation as a function of the average expansion.

6. CONCLUSIONS

Two interlaboratory studies were performed on RCA using the AMBT. The first study was performed with nine laboratories on a non-laboratory-created RCA designated as RCA-S at two aggregate proportions: 20% and 50% with the remainder being nonreactive aggregate. The second study was performed with 10 laboratories and 11 independent operators using two laboratory-created RCAs from Wyoming sources, Black Rock and Knife River, both of which had then been used as field specimens for six years before being broken and crushed for the study.

RCA-S is known to have been highly reactive through both visual inspection of the original concrete and RCA field specimen expansions. Results indicate that the expansions are NR based on the AMBT FHWA limits at 14 days and MR at 28 days. This aggregate also displayed similar expansions independent of the aggregate proportioning of RCA and nonreactive.

RCA-BR exhibited an increase in expansion when tested at proportions of 20% and 50% RCA. This is consistent with the behavior observed in Adams et al., 2013.

The RCA-KR tests did not indicate a correlation between RCA percentage and expansion, but instead demonstrated similar expansions independent of the aggregate proportioning of RCA and nonreactive fine.

Trends in whether an aggregate is deleteriously reactive or not can be influenced by the pessimum effect. How closely a reactive aggregate meets the criteria to achieve the maximum level of reactivity determines the reactivity classified as defined by limits in the AMBT, CPT, or FHWA

It has been observed consistently within this study that the RCA expansions in the AMBT have been less than the expansions seen in natural aggregate expansions. This is also observed in Li and Gress, 2006. These observations perpetuate the theory that an aggregate becomes more inert as the chemical reaction between the alkalis and the silicate runs its course. Furthermore, AMBT results provide insight into the risk of ASR when using RCA.

ASTM C1260 already designates a large acceptable difference between two laboratories at 43% of the mean expansion; however, tests performed within this study and the studies within Adams et al., 2013, indicate that RCA has significantly larger variability between tests within the laboratory and between laboratories than ASTM C1260 allows. This suggests that while ASTM C1260 is capable of testing for ASR in RCA, the precision limits of this standard should be modified to account for the variability found when using RCA.

The increased variation that is observed in ASR expansions with RCA could be due to the variable ratio of adhered mortar and exposed aggregate.

Finally, this study suggests that using RCA-BR and RCA-KR reduced ASR when combined with a locally sourced non-reactive aggregate. Although RCA-BR was reduced, expansions exceeded the expansion threshold of the AMBT. Both RCA-S and RCA-KR are considered innocuous based on the AMBT.

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APPENDIX

Table A.1 Additional materials used in field specimens

Specimen	Water (lb.)	NaOH (lb.)	Air Ent. (lb.)	Superplasticizer (lb.)	Slump (in.)	Air Content (%)
BHC-1	57.5	0	0.2	2.2	3	4.5
BHC-2	57.5	0	0.2	2.32	5.5	6
BHC-3	53.1	0.68	0.15	2.8	7.5	4.1
BHP-1	61.25	0	0.25	0	5	7
BHP-2	58	0	0.25	0	6	6
BHP-3	56.5	0.68	0.16	2.18	6.5	4.2
DF-1	57.5	0	0.25	0	3.5	5
DF-2	58	0	0.25	0	4.5	7
DF-3	57.5	0.68	0.24	2.74	4.5	5
GP-1	57.5	0	0.24	2.2	6.5	7.5
GP-2	53.4	0	0.2	2.2	4.5	4.5
GP-3	55.2	0.68	0.19	2.3	7	5.2
HP-1	57.5	0	0.25	0	2.5	5
HP-2	57.5	0	0.25	2.3	5.5	7
HP-3	57.5	0.68	0.24	2.44	3.5	5
KR-1	57.5	0	0.2	2.26	7.5	6.6
KR-2	49	0	0.2	2.3	5	4.7
KR-3	55	0	0.25	2.1	3.5	5
KR-4	55	0.68	0.25	2.3	4	8
LBG-1	60.4	0	0.25	0	0.5	4
LBG-2	65	0	0.25	0	2	4
LBG-3	65	0.68	0.25	0	6	6
LX-1	57.5	0	0.25	3	6	8
LX-2	53.9	0	0.25	2.4	8.5	9
LX-3	57.5	0.68	0.24	2.47	7.5	7.4
WOR-1	63	0	0.25	0	5.5	4.5
WOR-2	60.2	0	0.25	0	5	6
WOR-3	57.5	0.68	0.15	2.3	5.5	5.8

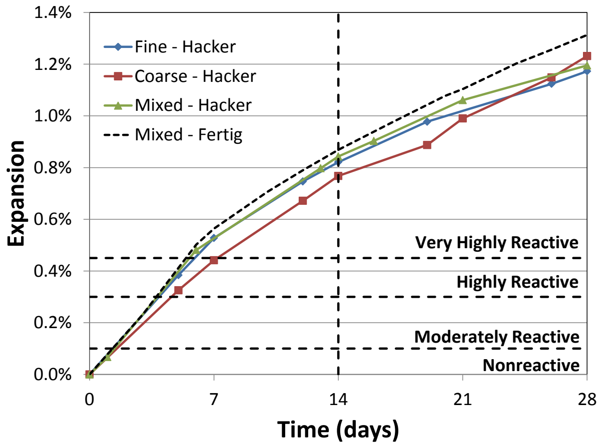

Figure A.1 AMBT results for natural Devries Farm Pit aggregate.

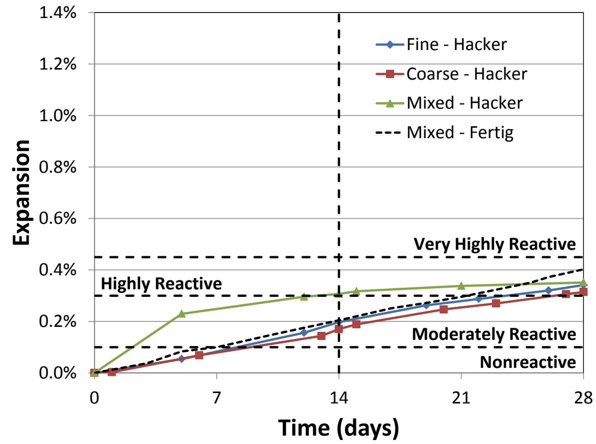

Figure A.4 AMBT results for natural Labarge aggregate.

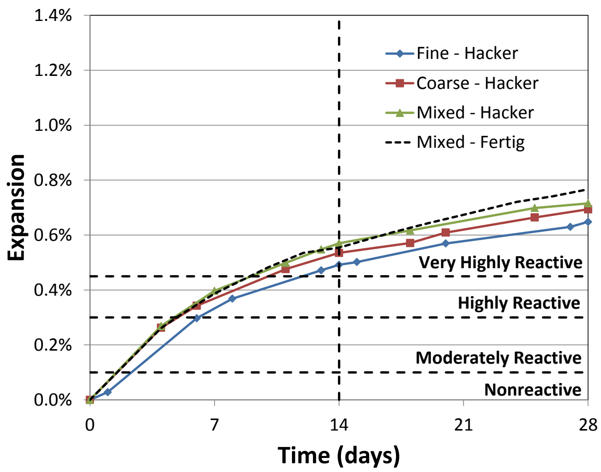

Figure A.2 AMBT results for natural Goton Pit aggregate.

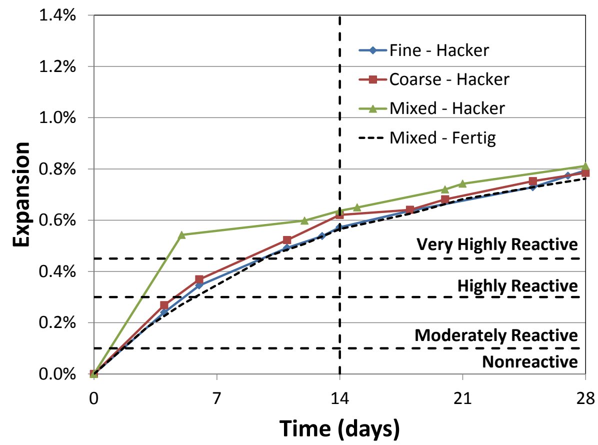

Figure A.5 AMBT results for natural Lamax aggregate.

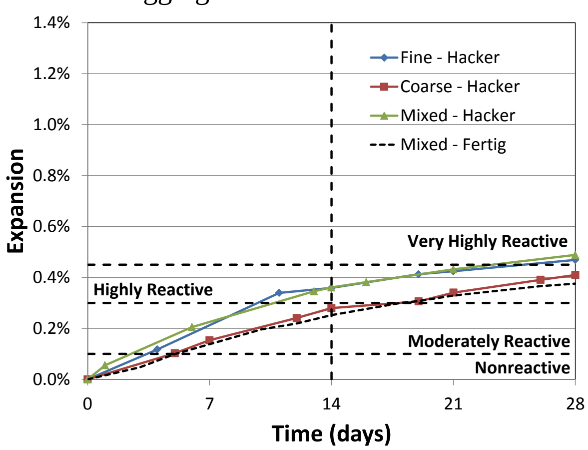

Figure A.3 AMBT results for natural Harris Pit aggregate.

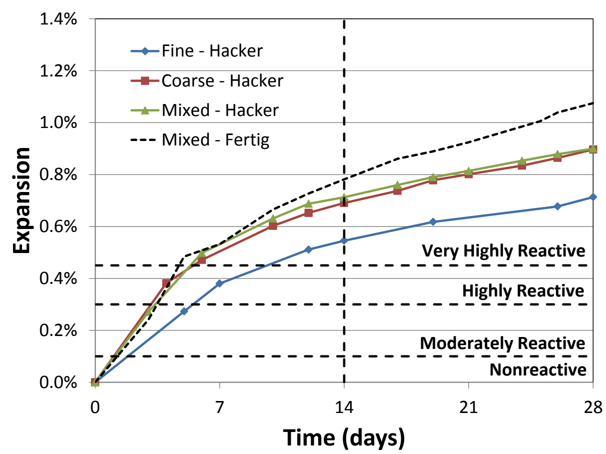

Figure A.6 AMBT results for natural Worland aggregate.

Table A.2 AMBT test results on natural aggregates

Source	Average Expansion (%)
BR	0.598
DF	0.844
GP	0.543
HP	0.299
KR	0.248
LBG	0.215
LX	0.588
WOR	0.716

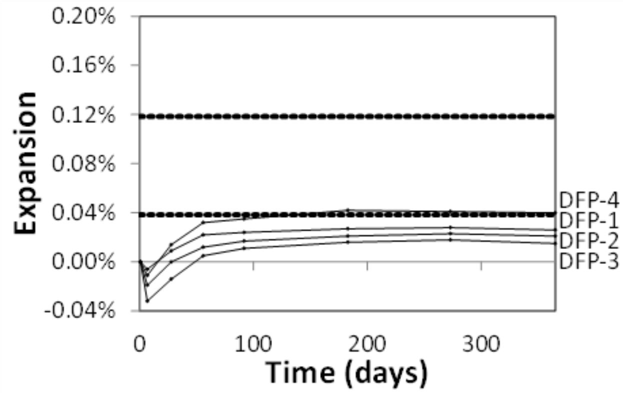

Figure A.7 CPT results for natural Devries Farm Pit aggregate.

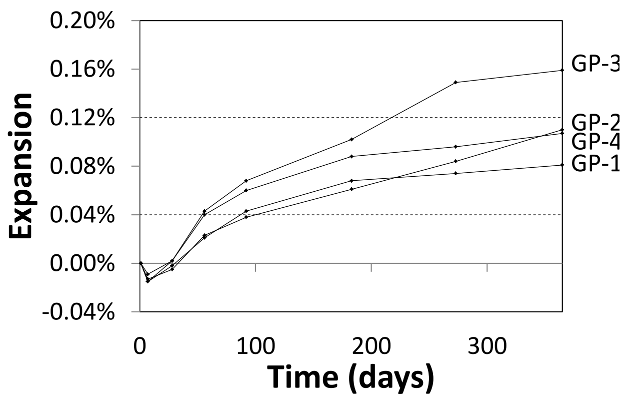

Figure A.8 CPT results for natural Goton Pit aggregate.

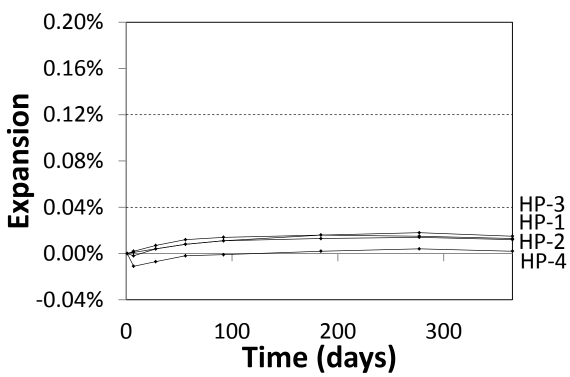

Figure A.9 CPT results for natural Harris Pit aggregate.

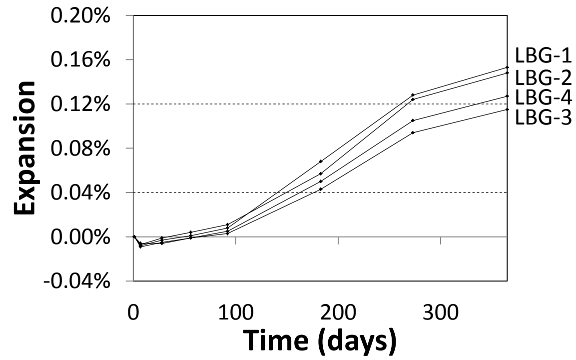

Figure A.10 CPT results for natural Labarge aggregate.

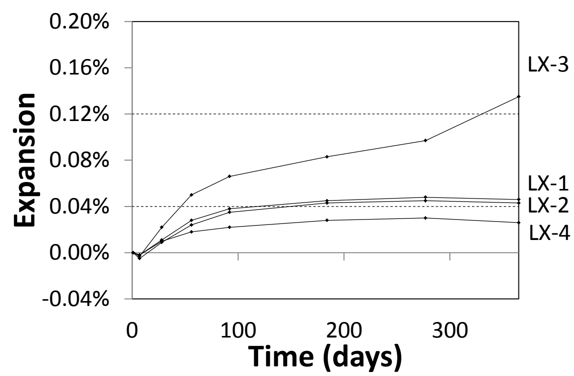

Figure A.11 CPT results for natural Lamax aggregate.

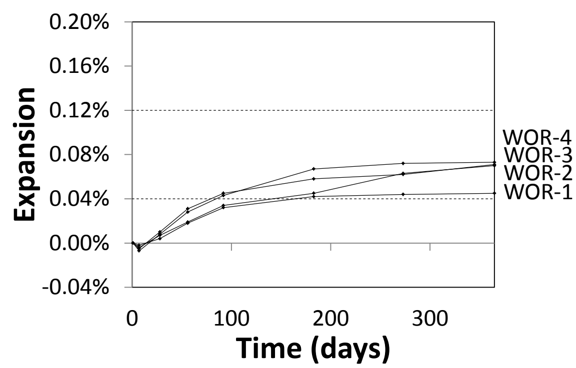

Figure A.12 CPT results for natural Worland aggregate.

Table A.3 CPT results on natural aggregates.

Source	Average Expansion (%)
BR	0.054
DF	0.026
GP	0.114
HP	0.011
KR	0.172
LBG	0.136
LX	0.063
WOR	0.065

Table A.4 Average AMBT results with RCA-20S

	Average Expansions								
	Laboratory								
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.013%	0.008%	0.010%	-0.003%	-0.005%	0.003%	0.005%	0.004%	0.006%
5	0.033%	0.007%	0.018%	-0.004%	0.005%	0.006%	0.017%	0.015%	0.012%
7	0.047%	0.026%	0.026%	0.008%	0.013%	0.009%	0.028%	0.023%	0.015%
9	0.069%	0.036%	0.033%	0.021%	0.025%	0.013%	0.035%	0.031%	0.039%
12	0.090%	0.052%	0.044%	0.036%	0.034%	0.021%	0.058%	0.052%	0.063%
14	0.106%	0.065%	0.052%	0.043%	0.052%	0.028%	0.074%	0.063%	0.074%
16	0.117%	0.072%	0.058%	0.052%	0.059%	0.035%	0.084%	0.073%	0.079%
19	0.135%	0.077%	0.068%	0.066%	0.077%	0.047%	0.098%	0.089%	0.088%
21	0.143%	0.089%	0.074%	0.070%	0.088%	0.056%	0.108%	0.099%	0.093%
23	0.154%	0.089%	0.076%	0.079%	0.094%	0.068%	0.112%	0.103%	0.098%
26	0.170%	0.098%	0.079%	0.087%	0.104%	0.085%	0.119%	0.110%	0.106%
28	0.181%	0.102%	0.084%	0.096%	0.111%	0.095%	0.123%	0.115%	0.111%

Table A.5 AMBT results for RCA-20S casting 1

	Expansions								
	Laboratory								
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.011%	0.012%	0.010%	-0.009%	-0.009%	0.004%	0.003%	0.003%	0.006%
5	0.034%	0.012%	0.019%	-0.007%	0.005%	0.007%	0.016%	0.016%	0.012%
7	0.048%	0.036%	0.026%	-0.001%	0.019%	0.010%	0.026%	0.026%	0.015%
9	0.073%	0.044%	0.033%	0.013%	0.026%	0.015%	0.033%	0.033%	0.039%
12	0.096%	0.062%	0.044%	0.023%	0.040%	0.022%	0.057%	0.057%	0.063%
14	0.115%	0.072%	0.052%	0.030%	0.054%	0.030%	0.073%	0.073%	0.074%
16	0.123%	0.077%	0.059%	0.036%	0.066%	0.038%	0.083%	0.083%	0.079%
19	0.142%	0.084%	0.070%	0.051%	0.078%	0.051%	0.098%	0.098%	0.088%
21	0.148%	0.097%	0.077%	0.058%	0.086%	0.060%	0.108%	0.108%	0.093%
23	0.161%	0.095%	0.079%	0.065%	0.096%	0.072%	0.112%	0.112%	0.098%
26	0.176%	0.101%	0.081%	0.073%	0.108%	0.090%	0.118%	0.118%	0.106%
28	0.185%	0.104%	0.086%	0.082%	0.115%	0.100%	0.122%	0.122%	0.111%

Table A.6 AMBT results for RCA-20S casting 2

	Expansions								
	Laboratory								
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	-
2	0.016%	0.004%	0.009%	0.003%	-0.001%	0.003%	0.006%	0.006%	-
5	0.032%	0.002%	0.018%	0.000%	0.004%	0.006%	0.019%	0.014%	-
7	0.046%	0.017%	0.026%	0.016%	0.006%	0.007%	0.030%	0.020%	-
9	0.065%	0.028%	0.033%	0.029%	0.023%	0.012%	0.037%	0.029%	-
12	0.085%	0.041%	0.044%	0.049%	0.028%	0.021%	0.059%	0.046%	-
14	0.097%	0.058%	0.051%	0.057%	0.050%	0.026%	0.074%	0.052%	-
16	0.111%	0.066%	0.057%	0.067%	0.052%	0.033%	0.084%	0.063%	-
19	0.127%	0.071%	0.066%	0.080%	0.075%	0.043%	0.099%	0.079%	-
21	0.138%	0.082%	0.071%	0.083%	0.090%	0.052%	0.109%	0.090%	-
23	0.147%	0.082%	0.072%	0.092%	0.093%	0.064%	0.113%	0.095%	-
26	0.163%	0.094%	0.076%	0.101%	0.101%	0.080%	0.119%	0.102%	-
28	0.176%	0.099%	0.081%	0.110%	0.107%	0.090%	0.124%	0.107%	-

Table A.7 Average AMBT results with RCA-50S

	Average Expansions								
	Laboratory								
Time (days)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.012%	-0.002%	0.007%	0.007%	0.003%	0.001%	0.005%	0.004%	0.005%
5	0.026%	-0.001%	0.017%	0.010%	0.005%	0.004%	0.015%	0.010%	0.014%
7	0.035%	0.004%	0.023%	0.019%	0.015%	0.007%	0.020%	0.016%	0.020%
9	0.055%	0.014%	0.030%	0.027%	0.019%	0.010%	0.024%	0.024%	0.034%
12	0.077%	0.027%	0.047%	0.042%	0.037%	0.015%	0.039%	0.039%	0.056%
14	0.091%	0.033%	0.053%	0.051%	0.043%	0.022%	0.049%	0.043%	0.070%
16	0.101%	0.042%	0.062%	0.062%	0.055%	0.025%	0.057%	0.052%	0.079%
19	0.122%	0.049%	0.077%	0.079%	0.068%	0.037%	0.069%	0.066%	0.092%
21	0.132%	0.061%	0.085%	0.089%	0.076%	0.044%	0.078%	0.075%	0.101%
23	0.141%	0.061%	0.086%	0.095%	0.085%	0.055%	0.082%	0.086%	0.107%
26	0.156%	0.070%	0.091%	0.108%	0.093%	0.071%	0.089%	0.101%	0.115%
28	0.166%	0.073%	0.093%	0.116%	0.098%	0.081%	0.094%	0.111%	0.121%

Table A.8 AMBT results for RCA-50S casting 1

	Expansions								
	Laboratory								
Time (days)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.010%	-0.002%	0.007%	0.009%	0.007%	0.003%	0.005%	0.004%	0.005%
5	0.027%	0.004%	0.017%	0.005%	0.003%	0.005%	0.015%	0.010%	0.014%
7	0.038%	0.009%	0.024%	0.019%	0.016%	0.007%	0.020%	0.016%	0.020%
9	0.058%	0.020%	0.030%	0.026%	0.019%	0.010%	0.024%	0.024%	0.034%
12	0.081%	0.033%	0.049%	0.043%	0.034%	0.016%	0.039%	0.039%	0.056%
14	0.094%	0.040%	0.055%	0.054%	0.038%	0.022%	0.049%	0.043%	0.070%
16	0.104%	0.049%	0.063%	0.064%	0.051%	0.025%	0.057%	0.052%	0.079%
19	0.121%	0.055%	0.079%	0.081%	0.071%	0.037%	0.070%	0.066%	0.092%
21	0.131%	0.067%	0.088%	0.091%	0.085%	0.044%	0.078%	0.075%	0.101%
23	0.137%	0.066%	0.089%	0.099%	0.092%	0.053%	0.083%	0.086%	0.107%
26	0.154%	0.074%	0.093%	0.110%	0.101%	0.069%	0.089%	0.101%	0.115%
28	0.162%	0.075%	0.099%	0.121%	0.106%	0.079%	0.094%	0.111%	0.121%

Table A.9 AMBT results for RCA-50S casting 2

	Expansions								
	Laboratory								
Time (days)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	-
2	0.014%	-0.001%	0.007%	0.006%	-0.002%	0.000%	0.006%	0.004%	-
5	0.025%	-0.006%	0.017%	0.015%	0.007%	0.004%	0.015%	0.010%	-
7	0.033%	0.000%	0.023%	0.019%	0.015%	0.007%	0.020%	0.016%	-
9	0.053%	0.009%	0.030%	0.028%	0.020%	0.010%	0.025%	0.024%	-
12	0.074%	0.021%	0.046%	0.041%	0.039%	0.014%	0.040%	0.039%	-
14	0.089%	0.026%	0.052%	0.049%	0.049%	0.022%	0.050%	0.043%	-
16	0.097%	0.035%	0.060%	0.061%	0.059%	0.026%	0.057%	0.052%	-
19	0.123%	0.042%	0.074%	0.078%	0.064%	0.037%	0.069%	0.066%	-
21	0.134%	0.055%	0.082%	0.088%	0.067%	0.045%	0.077%	0.075%	-
23	0.144%	0.056%	0.083%	0.092%	0.077%	0.057%	0.082%	0.086%	-
26	0.157%	0.066%	0.088%	0.105%	0.086%	0.072%	0.089%	0.101%	-
28	0.170%	0.072%	0.087%	0.111%	0.090%	0.083%	0.094%	0.111%	-

Table A.10 Average AMBT results for RCA-20BR

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.029%	0.014%	0.009%	0.009%	0.005%	0.011%	0.044%	0.012%	0.000%	0.013%
5	0.192%	0.130%	0.050%	0.058%	0.078%	0.084%	0.117%	0.062%	0.005%	0.051%
7	0.243%	0.179%	0.093%	0.122%	0.127%	0.146%	0.157%	0.103%	0.011%	0.078%
9	0.270%	0.227%	0.138%	0.168%	0.184%	0.199%	0.205%	0.133%	0.023%	0.141%
12	0.306%	0.272%	0.190%	0.205%	0.238%	0.257%	0.271%	0.193%	0.087%	0.185%
14	0.330%	0.274%	0.211%	0.225%	0.260%	0.287%	0.274%	0.224%	0.133%	0.215%
16	0.346%	0.285%	0.228%	0.240%	0.277%	0.309%	0.290%	0.240%	0.175%	0.236%
19	0.371%	0.304%	0.247%	0.264%	0.298%	0.339%	0.315%	0.261%	0.220%	0.262%
21	0.399%	0.310%	0.260%	0.277%	0.310%	0.354%	0.332%	0.275%	0.251%	0.271%
23	0.404%	0.330%	0.266%	0.281%	0.322%	0.368%	0.339%	0.289%	0.293%	0.281%
26	0.421%	0.335%	0.288%	0.302%	0.338%	0.381%	0.350%	0.300%	0.324%	0.297%
28	0.435%	0.351%	0.293%	0.311%	0.348%	0.396%	0.357%	0.320%	0.337%	0.300%

Table A.11 AMBT results for RCA-20BR casting 1

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.029%	0.003%	0.008%	0.011%	0.005%	0.015%	0.044%	0.012%	0.002%	0.013%
5	0.202%	0.090%	0.053%	0.066%	0.078%	0.068%	0.117%	0.062%	0.005%	0.051%
7	0.256%	0.145%	0.100%	0.122%	0.127%	0.127%	0.157%	0.103%	0.013%	0.078%
9	0.282%	0.184%	0.144%	0.165%	0.184%	0.185%	0.205%	0.133%	0.036%	0.141%
12	0.322%	0.218%	0.196%	0.201%	0.238%	0.249%	0.271%	0.193%	0.087%	0.185%
14	0.349%	0.233%	0.217%	0.220%	0.260%	0.282%	0.274%	0.224%	0.133%	0.215%
16	0.368%	0.250%	0.235%	0.236%	0.277%	0.305%	0.290%	0.240%	0.176%	0.236%
19	0.396%	0.262%	0.253%	0.256%	0.298%	0.338%	0.315%	0.261%	0.223%	0.262%
21	0.420%	0.271%	0.268%	0.269%	0.310%	0.354%	0.332%	0.275%	0.245%	0.271%
23	0.424%	0.291%	0.275%	0.273%	0.322%	0.369%	0.339%	0.289%	0.290%	0.281%
26	0.441%	0.295%	0.291%	0.292%	0.338%	0.384%	0.350%	0.300%	0.322%	0.297%
28	0.457%	0.310%	0.301%	0.300%	0.348%	0.399%	0.357%	0.320%	0.336%	0.300%

Table A.12 AMBT results for RCA-20BR casting 2

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	-	0.000%	-	-	0.000%	-
2	0.030%	0.025%	0.010%	0.007%	-	0.008%	-	-	-0.001%	-
5	0.182%	0.169%	0.047%	0.049%	-	0.100%	-	-	0.004%	-
7	0.230%	0.213%	0.087%	0.122%	-	0.165%	-	-	0.010%	-
9	0.257%	0.271%	0.133%	0.171%	-	0.214%	-	-	0.010%	-
12	0.289%	0.326%	0.184%	0.209%	-	0.265%	-	-	0.087%	-
14	0.311%	0.315%	0.206%	0.230%	-	0.292%	-	-	0.132%	-
16	0.325%	0.320%	0.221%	0.243%	-	0.313%	-	-	0.174%	-
19	0.346%	0.345%	0.241%	0.271%	-	0.340%	-	-	0.216%	-
21	0.379%	0.350%	0.252%	0.285%	-	0.354%	-	-	0.257%	-
23	0.384%	0.369%	0.258%	0.290%	-	0.366%	-	-	0.297%	-
26	0.401%	0.374%	0.285%	0.312%	-	0.379%	-	-	0.326%	-
28	0.413%	0.392%	0.285%	0.322%	-	0.394%	-	-	0.338%	-

Table A.13 Average AMBT results for RCA-50BR

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.053%	0.040%	0.015%	0.033%	0.013%	0.025%	0.067%	0.032%	0.012%	0.017%
5	0.276%	0.238%	0.095%	0.164%	0.164%	0.182%	0.163%	0.190%	0.068%	0.103%
7	0.359%	0.297%	0.156%	0.255%	0.264%	0.281%	0.269%	0.259%	0.171%	0.174%
9	0.391%	0.350%	0.205%	0.321%	0.318%	0.353%	0.374%	0.326%	0.265%	0.230%
12	0.443%	0.400%	0.260%	0.378%	0.385%	0.430%	0.480%	0.390%	0.362%	0.310%
14	0.477%	0.418%	0.283%	0.407%	0.415%	0.470%	0.489%	0.435%	0.406%	0.340%
16	0.499%	0.435%	0.303%	0.426%	0.440%	0.500%	0.508%	0.467%	0.435%	0.368%
19	0.531%	0.453%	0.328%	0.464%	0.471%	0.540%	0.537%	0.506%	0.474%	0.405%
21	0.564%	0.472%	0.337%	0.482%	0.490%	0.559%	0.556%	0.530%	0.504%	0.419%
23	0.571%	0.478%	0.354%	0.490%	0.506%	0.579%	0.565%	0.550%	0.529%	0.437%
26	0.592%	0.498%	0.374%	0.521%	0.527%	0.600%	0.578%	0.568%	0.552%	0.457%
28	0.607%	0.513%	0.381%	0.534%	0.541%	0.619%	0.587%	0.590%	0.566%	0.469%

Table A.14 AMBT results for RCA-50BR casting 1

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.052%	0.020%	0.014%	0.012%	0.013%	0.024%	0.067%	0.032%	0.010%	0.017%
5	0.275%	0.193%	0.094%	0.141%	0.164%	0.164%	0.163%	0.190%	0.066%	0.103%
7	0.357%	0.268%	0.153%	0.233%	0.264%	0.265%	0.269%	0.259%	0.162%	0.174%
9	0.385%	0.319%	0.202%	0.301%	0.318%	0.341%	0.374%	0.326%	0.260%	0.230%
12	0.436%	0.381%	0.257%	0.360%	0.385%	0.422%	0.480%	0.390%	0.360%	0.310%
14	0.471%	0.395%	0.279%	0.388%	0.415%	0.464%	0.489%	0.435%	0.403%	0.340%
16	0.494%	0.428%	0.298%	0.407%	0.440%	0.497%	0.508%	0.467%	0.436%	0.368%
19	0.529%	0.436%	0.323%	0.446%	0.471%	0.540%	0.537%	0.506%	0.478%	0.405%
21	0.563%	0.459%	0.333%	0.460%	0.490%	0.562%	0.556%	0.530%	0.504%	0.419%
23	0.570%	0.472%	0.350%	0.472%	0.506%	0.582%	0.565%	0.550%	0.528%	0.437%
26	0.592%	0.487%	0.369%	0.503%	0.527%	0.606%	0.578%	0.568%	0.555%	0.457%
28	0.608%	0.510%	0.375%	0.516%	0.541%	0.625%	0.587%	0.590%	0.566%	0.469%

Table A.15 AMBT results for RCA-50BR casting 2

	Expansion									
	Laboratory									
Time (Days)	1	2	3	4	5	6	8	9	10	11
0	0.000%	0.000%	0.000%	0.000%	-	0.000%	-	-	0.000%	-
2	0.054%	0.060%	0.016%	0.054%	-	0.027%	-	-	0.013%	-
5	0.277%	0.283%	0.095%	0.187%	-	0.201%	-	-	0.069%	-
7	0.361%	0.325%	0.159%	0.276%	-	0.298%	-	-	0.180%	-
9	0.398%	0.382%	0.207%	0.341%	-	0.365%	-	-	0.271%	-
12	0.449%	0.420%	0.264%	0.397%	-	0.437%	-	-	0.364%	-
14	0.483%	0.441%	0.288%	0.426%	-	0.475%	-	-	0.408%	-
16	0.503%	0.443%	0.307%	0.445%	-	0.503%	-	-	0.434%	-
19	0.534%	0.469%	0.333%	0.483%	-	0.540%	-	-	0.470%	-
21	0.565%	0.486%	0.341%	0.503%	-	0.556%	-	-	0.503%	-
23	0.572%	0.483%	0.358%	0.509%	-	0.576%	-	-	0.529%	-
26	0.593%	0.509%	0.378%	0.539%	-	0.593%	-	-	0.549%	-
28	0.606%	0.515%	0.386%	0.551%	-	0.613%	-	-	0.565%	-

Table A.16 Average AMBT results for RCA-20KR

	Average Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.014%	0.003%	0.007%	-0.002%	0.001%	0.005%	0.010%	0.007%	-0.002%	-0.003%
5	0.029%	0.027%	0.009%	0.012%	0.015%	0.023%	0.023%	0.012%	-0.001%	0.013%
7	0.046%	0.033%	0.016%	0.017%	0.025%	0.036%	0.033%	0.020%	0.003%	0.022%
9	0.062%	0.050%	0.026%	0.028%	0.037%	0.049%	0.048%	0.012%	0.009%	0.036%
12	0.087%	0.060%	0.033%	0.038%	0.049%	0.066%	0.079%	0.050%	0.018%	0.041%
14	0.103%	0.070%	0.041%	0.047%	0.061%	0.074%	0.080%	0.060%	0.025%	0.053%
16	0.115%	0.094%	0.047%	0.056%	0.071%	0.091%	0.088%	0.077%	0.036%	0.059%
19	0.133%	0.093%	0.056%	0.074%	0.083%	0.106%	0.100%	0.094%	0.056%	0.068%
21	0.154%	0.103%	0.063%	0.081%	0.096%	0.113%	0.108%	0.106%	0.066%	0.070%
23	0.164%	0.110%	0.066%	0.082%	0.098%	0.120%	0.113%	0.111%	0.089%	0.076%
26	0.181%	0.116%	0.079%	0.100%	0.112%	0.129%	0.121%	0.119%	0.102%	0.082%
28	0.193%	0.125%	0.084%	0.105%	0.122%	0.134%	0.126%	0.128%	0.112%	0.085%

Table A.17 AMBT results for RCA-20KR casting 1

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.015%	0.004%	0.006%	-0.004%	0.001%	0.006%	0.010%	0.007%	-0.001%	-0.003%
5	0.027%	0.027%	0.011%	0.015%	0.015%	0.024%	0.023%	0.012%	-0.001%	0.013%
7	0.042%	0.031%	0.017%	0.016%	0.025%	0.037%	0.033%	0.020%	0.002%	0.022%
9	0.059%	0.041%	0.027%	0.026%	0.037%	0.049%	0.048%	0.012%	0.005%	0.036%
12	0.085%	0.052%	0.034%	0.036%	0.049%	0.068%	0.079%	0.050%	0.012%	0.041%
14	0.103%	0.056%	0.042%	0.043%	0.061%	0.072%	0.080%	0.060%	0.018%	0.053%
16	0.116%	0.060%	0.049%	0.051%	0.071%	0.093%	0.088%	0.077%	0.033%	0.059%
19	0.136%	0.065%	0.058%	0.074%	0.083%	0.107%	0.100%	0.094%	0.045%	0.068%
21	0.159%	0.075%	0.065%	0.080%	0.096%	0.113%	0.108%	0.106%	0.060%	0.070%
23	0.167%	0.081%	0.068%	0.081%	0.098%	0.121%	0.113%	0.111%	0.080%	0.076%
26	0.186%	0.086%	0.081%	0.097%	0.112%	0.130%	0.121%	0.119%	0.093%	0.082%
28	0.197%	0.098%	0.086%	0.102%	0.122%	0.133%	0.126%	0.128%	0.106%	0.085%

Table A.18 AMBT results for RCA-20KR casting 2

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	-	0.000%	-	-	0.000%	-
2	0.014%	0.002%	0.007%	0.000%	-	0.003%	-	-	-0.003%	-
5	0.030%	0.027%	0.007%	0.009%	-	0.021%	-	-	0.000%	-
7	0.050%	0.035%	0.014%	0.019%	-	0.036%	-	-	0.004%	-
9	0.065%	0.059%	0.025%	0.030%	-	0.049%	-	-	0.013%	-
12	0.088%	0.067%	0.032%	0.040%	-	0.063%	-	-	0.024%	-
14	0.103%	0.083%	0.039%	0.051%	-	0.075%	-	-	0.032%	-
16	0.114%	0.128%	0.046%	0.060%	-	0.089%	-	-	0.039%	-
19	0.131%	0.120%	0.053%	0.073%	-	0.106%	-	-	0.067%	-
21	0.148%	0.131%	0.061%	0.083%	-	0.113%	-	-	0.072%	-
23	0.160%	0.139%	0.064%	0.084%	-	0.118%	-	-	0.098%	-
26	0.176%	0.146%	0.076%	0.103%	-	0.128%	-	-	0.110%	-
28	0.189%	0.153%	0.081%	0.108%	-	0.134%	-	-	0.117%	-

Table A.19 Average AMBT results for RCA-50KR

	Expansion									
	Laboratory									
Time (Days)	1	2	3	4	5	6	8	9	10	11
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.015%	0.006%	0.002%	0.003%	0.001%	0.006%	0.004%	0.009%	0.011%	0.006%
5	0.036%	0.031%	0.009%	0.017%	0.015%	0.022%	0.011%	0.025%	0.007%	0.016%
7	0.058%	0.036%	0.020%	0.024%	0.023%	0.036%	0.040%	0.034%	0.010%	0.021%
9	0.077%	0.052%	0.024%	0.035%	0.036%	0.049%	0.063%	0.036%	0.015%	0.026%
12	0.100%	0.064%	0.034%	0.040%	0.055%	0.067%	0.104%	0.070%	0.026%	0.049%
14	0.116%	0.067%	0.041%	0.055%	0.059%	0.081%	0.100%	0.082%	0.033%	0.054%
16	0.127%	0.083%	0.045%	0.061%	0.062%	0.094%	0.109%	0.088%	0.039%	0.061%
19	0.143%	0.080%	0.053%	0.065%	0.079%	0.108%	0.124%	0.109%	0.061%	0.073%
21	0.154%	0.085%	0.054%	0.077%	0.088%	0.116%	0.133%	0.120%	0.080%	0.077%
23	0.167%	0.090%	0.060%	0.083%	0.094%	0.124%	0.136%	0.124%	0.093%	0.081%
26	0.182%	0.098%	0.069%	0.089%	0.099%	0.130%	0.141%	0.131%	0.104%	0.088%
28	0.192%	0.102%	0.074%	0.097%	0.102%	0.139%	0.144%	0.143%	0.116%	0.094%

Table A.20 AMBT results for RCA-50KR casting 1

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
2	0.014%	0.004%	0.002%	0.002%	0.001%	0.006%	0.004%	0.009%	0.022%	0.006%
5	0.036%	0.029%	0.009%	0.015%	0.015%	0.022%	0.011%	0.025%	0.009%	0.016%
7	0.057%	0.039%	0.019%	0.022%	0.023%	0.036%	0.040%	0.034%	0.012%	0.021%
9	0.076%	0.046%	0.023%	0.033%	0.036%	0.050%	0.063%	0.036%	0.018%	0.026%
12	0.099%	0.063%	0.032%	0.035%	0.055%	0.066%	0.104%	0.070%	0.029%	0.049%
14	0.115%	0.062%	0.037%	0.050%	0.059%	0.077%	0.100%	0.082%	0.036%	0.054%
16	0.126%	0.069%	0.041%	0.056%	0.062%	0.092%	0.109%	0.088%	0.042%	0.061%
19	0.143%	0.073%	0.048%	0.058%	0.079%	0.107%	0.124%	0.109%	0.066%	0.073%
21	0.153%	0.078%	0.048%	0.072%	0.088%	0.114%	0.133%	0.120%	0.086%	0.077%
23	0.164%	0.085%	0.054%	0.078%	0.094%	0.122%	0.136%	0.124%	0.098%	0.081%
26	0.181%	0.089%	0.062%	0.085%	0.099%	0.129%	0.141%	0.131%	0.113%	0.088%
28	0.191%	0.098%	0.066%	0.092%	0.102%	0.135%	0.144%	0.143%	0.120%	0.094%

Table A.21 AMBT results for RCA-50KR casting 2

	Expansion									
	Laboratory									
Time (Days)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
0	0.000%	0.000%	0.000%	0.000%	-	0.000%	-	-	0.000%	-
2	0.017%	0.007%	0.002%	0.003%	-	0.006%	-	-	0.001%	-
5	0.035%	0.034%	0.009%	0.019%	-	0.022%	-	-	0.006%	-
7	0.058%	0.032%	0.021%	0.026%	-	0.035%	-	-	0.008%	-
9	0.077%	0.058%	0.026%	0.038%	-	0.048%	-	-	0.013%	-
12	0.101%	0.066%	0.037%	0.045%	-	0.069%	-	-	0.023%	-
14	0.116%	0.072%	0.044%	0.059%	-	0.085%	-	-	0.029%	-
16	0.127%	0.096%	0.049%	0.066%	-	0.096%	-	-	0.035%	-
19	0.143%	0.088%	0.059%	0.071%	-	0.110%	-	-	0.055%	-
21	0.156%	0.093%	0.060%	0.082%	-	0.117%	-	-	0.074%	-
23	0.169%	0.095%	0.067%	0.088%	-	0.126%	-	-	0.087%	-
26	0.182%	0.106%	0.076%	0.092%	-	0.132%	-	-	0.095%	-
28	0.193%	0.107%	0.082%	0.103%	-	0.142%	-	-	0.112%	-