Applicability of Standard Alkali-Silica Reactivity Testing Methods for Recycled Concrete Aggregate

Matthew P. Adams [1*], Brian Gray[1], Jason H. Ideker[1], Jennifer E. Tanner[2], Angela Jones[2], Benoit Fournier[3], Sean Beauchemin[3], Medhat Shehata[4], Robert Johnson[4]

[1]Oregon State University, Corvallis, OR, USA

[2]University of Wyoming, Laramie, WY, USA

[3]Université Laval, Québec, Québec, Canada

[4]Ryerson University, Toronto, Ontario, Canada

Abstract

Replacing natural aggregate with recycled concrete aggregate (RCA) in new concrete is severely hindered by a lack of technical information on long-term durability of this concrete. The goal of this project was to determine whether current testing methods (namely the Accelerated Mortar Bar Test ASTM C 1260 (AMBT)) for assessing virgin aggregate susceptibility to alkali-silica reactivity could be used to assess the potential reactivity of concrete incorporating RCA.) RCA containing four different original reactive aggregates were investigated. The AMBT was effective in detecting reactivity but expansion varied based on RCA processing. Depending on the aggregate type and the extent of processing, up to a 100% increase in expansion was observed. Replicate testing was performed at four university laboratories using the same RCA sources to evaluate repeatability and consistency of results. The authors recommend a change to precision and bias statements in AMBT when testing the reactivity of RCA.

Keywords: Recycled Concrete Aggregate, Sustainable Construction, Alkali-Silica Reactivity

1 INTRODUCTION

Recycled concrete aggregate (RCA) is predominately limited to use as pavement base and sub-base, or non-structural fill in the United States (U.S.). An estimated 150 million tons of construction waste is generated each year in the U.S., with concrete debris making up about 50% of this material. Of that, roughly 75 million tons of concrete debris produced each year, almost 60% is placed into landfills [1]. As construction prices and the demand for sustainable solutions increase, the opportunity to use this RCA in new concrete will also increase. Previous studies have shown that recycled concrete aggregate (RCA) can effectively be used to produce the same, or even increased concrete strength and flexural performance in new concretes [2-4]. However, use of the material is still hindered by the lack of widespread technical information on the long-term durability of concrete made with new concrete. A U.S. Federal Highway Administration report in 2004 identified the need for further information on whether typical durability test methods for virgin aggregate could apply to RCA [5] and Melton identified a specific need for more research concerning the use of RCA that is affected by alkali-silica reaction (ASR) [6].

* Correspondence to: matthewpadams@gmail.com

Previous work done by Scott and Gress shows that RCA created from concrete damaged by ASR can be reactive [7]. However, this work used a heavily modified version of the AMBT test due to a concern that the required gradation of aggregates for the test will destroy the integrity of the RCA. Shehata et al. (2010) showed that the AMBT could be used to detect reactivity [8]; however, only one aggregate source was investigated in one laboratory. The authors also observed that an increase in aggregate processing (i.e. fine material recovered from the large scale crushing operations used to produce coarse RCA versus fine material obtained from crushing coarse RCA in the laboratory) affected the alkali-silica reactivity of the RCA, with further processed aggregates having higher expansions [8]. In this study four concrete sources, each incorporating a different alkali-silica reactive aggregate, were investigated at four different laboratories: University of Wyoming (UW), Ryerson University (RU), Oregon State University (OSU), and Université Laval (UL). The use of four laboratories allowed for the verification of multi-laboratory precision standards required by the AMBT standard used in the U.S., ASTM C 1260, for mortar bars containing RCA. This manuscript presents the results of using the AMBT to evaluate the alkali-silica reactivity of RCA specifically focusing on repeatability of results and modifications to the standard AMBT.

2 MATERIALS AND METHODS

2.1 Materials

Aggregates

Four different recycled concrete aggregates were obtained for this study. Each aggregate was produced from the crushing of outdoor exposure blocks that were used as part of a long-term aggregate alkali-silica reactivity testing and correlation study performed at CANMET, in Ottawa, Canada[9]. These exposure blocks were cast under controlled laboratory conditions and measured nominally 380 mm x 380 mm x 710 mm and were then exposed to outdoor environmental conditions at that location. The blocks that were chosen to use as recycled concrete aggregates for this study were selected for their age, extent of alkali-silica damage, and variation in mineralogy of reactive virgin aggregates. Further information about these exposure blocks can be seen in Table 1 [9]. All four laboratories involved in the multi-laboratory study received portions of the crushed concrete blocks incorporating the following original/virgin aggregates: Alberta, Potsdam, Springhill and Bernier. The aggregate materials provided consisted of 1) fine material recovered from the large scale crushing operations used to produce coarse RCA (called "crusher's fines") and 2) coarse RCA (5 to 20 mm in size) that would be used to further produce fine material in the laboratory for mortar bar testing.

Cement

All four laboratories involved in this study used the same control cement for the multi-laboratory testing that was performed. This was done in order to determine the reproducibility of the ASR test methods used as part of this research. This resulted in testing differences occurring only through individual lab equipment and researchers preparing, monitoring and analyzing the samples. Table 2 shows the oxide analysis for the CANMET cement used in this research.

2.2 Accelerated Mortar Bar Test

The AMBT indicates an aggregate's potential alkali-silica reactivity through the expansion of mortar bars created from that aggregate. Various agencies each set their own expansion limits for an aggregate to qualify as innocuous when using the AMBT; for the purpose of this study, however, mortar bars that expanded above 0.10% at 14 days after submersion in 1N NaOH solution at 80 ± 2 °C indicated a reactive aggregate. Expansions of mortar bars were measured out to 28 days, though the 14-day limit was used to indicate reactivity. The AMBT standard used as part of this study, ASTM C 1260 states that, for materials with an average expansion greater than 0.10% at 14 days, the results of tests conducted on the same aggregate should not differ from the mean expansion by more than 43%. This standard also states that the multi-laboratory coefficient of variation for the aggregates should be 15.2% [10].

Standard properties of the RCA were characterized for the AMBT including absorption capacity, gradation after various crushing operations and specific gravity. RCA consists of four phases: cement paste, virgin fine aggregate, virgin course aggregate (whole and fractured), and air voids. Due to the presence of the cement paste and the air voids in the RCA, it was important to verify if typical standards could be used to determine the absorption capacity of the RCA. Several standard procedures were modified as part of this study in order to correctly appraise the potential alkali-reactivity of the RCA: the aggregate washing procedures, the absorption capacity test, and the mortar bar mixing procedure. The modifications made to the procedures are outlined below. Each laboratory in the multi-laboratory study used all modifications to the aggregate preparation, tests and procedures.

Aggregate Preparation

The AMBT requires a specific gradation of fine aggregates for the mortar mixture. The gradation requirements for AMBT can be seen in the Table 3. For the RCA to reach these gradations, it must be mechanically crushed down to the required sizes. Work performed by Shehata et al. [8] showed that an increase in the level of crushing could affect the reactivity results of the aggregate in the AMBT test. In order to address this issue, two different levels of crushing were employed to prepare the aggregate. The exposure blocks were broken apart into 100-150 cm (nominal) pieces through use of mechanical means. These pieces were then shipped to a pilot scale crushing operation which would crush the recycled concrete into a gradation ranging from, nominally, 0.15 to 19 mm. Material that met the size requirements for the AMBT test from the pilot scale crushing procedure (i.e. < 4.75mm) was put aside and will herein be referred to as "crusher's fines". Material that was larger than the AMBT gradation requirements (i.e. from 4.75 to 19mm in size) was then crushed again using individual laboratory small-scale jaw crushers to the appropriate gradation. RCA obtained from in-laboratory crushing procedures will be referred to as "re-crushed". Generally, the crusher's fines were observed to have higher paste content, whereas the re-crushed aggregate had a more even distribution of paste and virgin aggregate.

Aggregate Washing

Modifications to the aggregate washing procedure were necessary prior to incorporating RCA into the sample mixtures. Standard practice provides that the aggregates shall be washed over a finer screen size than the aggregate's gradation until the water runs clear. When attempting to do this with the RCA, it was observed that the wash water never ran clear. A prolonged washing period may further erode the cement paste attached to virgin aggregates in the RCA, hydrate unhydrated cement particles in the RCA and/or leach calcium or alkalis from the aggregates and the cement paste. The modified washing procedure used is shown below:

- Sieve aggregate, and keep separated according to each fraction retained on sieve sizes;
- Measure out about 1500 g of material onto a fine sieve;
- Wash aggregate using a rubber hose with a fanned-spray hose nozzle for the times allotted below for each retained on sieve size:
    - #8 Sieve: 3 minutes 30 seconds
    - #16 Sieve: 5 minutes
    - #30 Sieve: 6 minutes

- #50 Sieve: 7 minutes
- #100 Sieve: 8 minutes

- Place aggregates into a 110 °C oven to dry for 24 +/- 2 hours before using.

Absorption Capacity

Due to the high absorption capacity of the RCA compared to virgin aggregates, it was necessary to check the absorption of the RCA at varied time periods to ensure full saturation before determining the absorption capacity of the RCA. In order to find the appropriate soaking time for the absorption capacity test, a laboratory-created RCA was used to measure the typical absorption rate of RCA. The RCA was soaked for 24, 48 and 72 hour periods, and the absorption capacity was checked for each soak time. The RCA reached 95% of its absorption capacity within 24 hours of soaking and exhibited minimal gain in water uptake at 48 and 72 hours. It was also determined that the RCA reached 85% of its total absorption capacity after 30 minutes of soaking. The 24-hour soaking period determined to reach 95% absorption capacity was then used to find the absorption capacity of each RCA used in this study.

Mortar Bar Mixing Procedure

The standard mortar mixing procedure for the AMBT states that the mixing water be placed in the bottom of a 5L commercial type three speed mixer, with the cement being placed on top. This then soaks for 30 seconds prior to mixing in the aggregate [11]. However, because of the high absorption capacity of the RCA, it was necessary to modify the mixing procedure so the aggregates could presoak to reach absorption close to saturated surface dry. This was determined to require a soak time of 30 minutes. The modified mixing procedure follows:

- After washing and drying the aggregate, soak in the mixing water, which is corrected for 95% of the aggregate absorption, for a period of 30 minutes
- Mix soaked aggregate for 30 seconds in mixer on low speed
- Slowly add cement over a 30 second period while mixing on low speed
- Stop the mixer and let the mortar stand for 1 minute 30 seconds. During the first 15 seconds of this rest period, scrape down into the mixture any mortar that may have collected on the side of the bowl; then cover the bowl with a lid
- Finish mixing the mortar on medium speed for 1 minute
- Cast specimens

Testing Program

The testing program for the multi-laboratory study was performed to observe the repeatability of the AMBT test between laboratories, the effect of different replacement percentages of RCA for the non-reactive aggregate, and to observe the reactivity difference between the crusher's fine and the re-crushed RCA. Specimens with 100% RCA, 50% RCA and 25% RCA were cast for both the crusher's fines and re-crushed coarse RCA with non-reactive natural sand provided by CANMET being used for the remaining portion of the material required for the mixture. Each mortar bar set was cast with a water-to-cement ratio of 0.47, total aggregate content (by mass) of 990 g and total cement content of 440 g. The RCA replaced the non-reactive sand at the aforementioned percentages by mass. The number of AMBT mortar bar sets cast by each laboratory can be seen in

Table 4.

RESULTS

Figure 1 shows the expansion of mortar specimens up to 28 days for re-crushed RCA at a 100% replacement level for the Alberta, Bernier, Potsdam and Springhill aggregates tested at the OSU laboratory. The Springhill, Alberta, and Bernier re-crushed RCA mortar bars all exceed the AMBT limit of 0.10% at 14 days, the Potsdam re-crushed RCA mortar bar does not reach the 0.10% expansion limit by day 14 which would classify the aggregate as a nonreactive aggregate according to AMBT. It should be noted that the Potsdam aggregate is a siliceous sandstone that generates low expansion in the AMBT (see Table 1). This is due to the crushing process that eliminates the reactive siliceous phase from the size fractions used for mortar bar testing [12].

Figure 2 shows the expansion of mortar specimens up to 28 days for crusher's fines RCA at a 100% replacement level for the Alberta, Bernier, Potsdam, and Springhill aggregates tested at the OSU laboratory. Here, the Alberta crusher's fines RCA mortar bar is the only sample set to exceed the AMBT limit of 0.10% expansion limit by day 14. This figure also shows that the Bernier, Potsdam, and Springhill crusher's fines RCA mortar bars do not reach the 0.10% expansion limit by day 14, which would classify the aggregates as nonreactive according to AMBT. The Potsdam and Springhill RCA do, however, exceed the 0.10% limit by day 28; however this does not change their classification as a nonreactive aggregate according to ASTM C 1260 (the standard used as part of this study), the expansion limit is specified at 14 days after exposure to NaOH.

Figure 3 shows the average AMBT expansion for each replacement level of re-crushed and crusher's fines RCA for each aggregate type (Alberta, Bernier, Potsdam, and Springhill) across all four laboratories in the multi-laboratory study. The expansion levels generally increase as the aggregate processing level increases with the re-crushed RCA results showing higher expansion levels than the crusher's fines RCA AMBTs. The Springhill and Alberta RCAs show a significant increase in expansion (over 100% increase in expansion at 100% replacement levels for both aggregates) whereas the Bernier exhibits a much smaller increase in expansion. The Potsdam aggregate, however shows no increase in expansion at the 100% replacement level and exhibits a decrease in expansion at 25% and 50% replacement levels. In Figure 3 it can be observed, as well, that all four aggregates show that the expansion increase between different levels of processing decreases as the aggregate replacement level decreases.

Table 5 and Table 6 show the mean expansion in the AMBT for each RCA replacement levels and aggregate type, the coefficient of variation for that set, the precision boundary (43% above or below the mean expansions according to ASTM C 1260) and outliers from the precision boundary for that set for the re-crushed RCA and the crusher's fines RCA, respectively. All but one replacement level and aggregate type fell within the 43% precision limits used for this study. The 50% RCA replacement of the Alberta aggregate is shown as the sole outlier. The coefficient of variation (COV) varied greatly between tests ranging from 5.8% to 22.8% for the re-crushed RCA AMBT sets, and from 10.8% to 27.6% for the crusher's fines RCA AMBT sets. The highest observed overall, 27.6%, was for the 50% RCA replacement of the Alberta aggregate, which coincides with the single test not meeting the precision limits.

3 DISCUSSION

Each recycled concrete aggregate type presented here exhibited an increase in expansion as its replacement level in the AMBT was increased (from 25 to 50 to 100%). This can be seen in the tests with both the re-crushed RCA and the crusher's fines RCA (Figure 3). This is logical as it corresponds to an increase in the virgin reactive aggregate content in the mortar bar. The general increase in expansion concurrent with increases in RCA replacement levels indicates that for higher replacement levels of reactive RCA increasing levels of mitigation measures may be necessary to prevent the risk of deleterious ASR.

In general, the Springhill and Alberta RCA's showed the highest expansions using the re-crushed aggregate at all replacement levels, with the Springhill RCA also exhibiting the highest expansion using the crusher's fines aggregate at each replacement level (see Figure 3). As seen in Table 1, the virgin Springhill aggregate exhibited a very high reactivity according to the accelerated mortar bar test (AMBT) and concrete prism test (CPT); this high level of reactivity continues to cause expansion when the concrete created with the Springhill aggregate is used as an RCA. The Alberta virgin aggregate, however, is only classified as a moderately reactive aggregate in the CPT; however, it generates significant expansion (0.36%) in the AMBT. The high expansion of the Alberta RCA is very much in line with the high levels of expansion measured on the virgin aggregate in the AMBT. The high expansion of the Alberta RCA could also indicate that the adhered mortar was easily removed in the crushing process or that the virgin aggregate within the RCA broke down easily during the RCA crushing procedures. As the aggregate is processed, adhered mortar may be removed from the system because fracture will likely occur first along the cement-aggregate bonds, which will increase the amount of virgin aggregate that is used as RCA in the mortar bar. The amount of adhered mortar removed increases as the level of processing increases. This is particularly the case for the Alberta aggregate, which is a natural gravel and has a large proportion of well-rounded particles. Also, further processing will likely cause new cracks or fracture surfaces to appear in the original aggregate in the RCA. This may cause newly exposed surfaces, which could increase the available silica in the aggregate and lead to an increase in expansion. In order to better understand the differences in the expansion between the crusher's fines and the re-crushed RCA aggregates, a petrographic examination of the above aggregate materials was carried out and the data are presented in the paper by Beauchemin and Fournier (2012), also in this 14th ICAAR conference proceedings.

The expansion increased for each of the RCA types, except Potsdam, as the aggregate processing level increased (i.e. the expansion with re-crushed material was greater than the expansion with crusher's fines). This confirms that different levels of crushing can affect the expansion levels observed in the AMBT test. This increase in expansion could be explained by an increase in available silica in the re-crushed aggregates. The increase in expansion of the re-crushed aggregate over the crusher's fines aggregate could pose issues for aggregate testing prior to their use in large-scale RCA replacement operations. Re-crushed aggregate will offer a better representation of field conditions because the virgin aggregate content of the re-crushed RCA is more likely to represent that of the coarse aggregate used in new concrete.

All but one sample set met the multi-laboratory precision boundary limits that were used as a part of this study. This confirms that the precision limits stated in the ASTM C 1260 test may be applicable for use with RCA. The multi-laboratory coefficient of variation observed in this test, however, does not match the 15.2% provided in the ASTM C 1260. The crusher's fines RCA sets also showed a significantly higher average COV than the re-crushed RCA. This difference in COV between the crusher's fines and the re-crushed RCA can be attributed to the more uniform aggregate received through the re-crushing process. The average COV will change depending on adhered mortar content and the level of processing used in the aggregate; thus the COV statement in the ASTM C 1260 test should be relaxed to take this into account when using RCA.

4 CONCLUSIONS

The research presented herein demonstrated that the AMBT test could be used to assess the potential alkali-reactivity of recycled concrete aggregates. The following conclusions were made based on this research:

- The absorption capacity testing required at least a 24 hour soaking period to take up 95% of the RCA material absorption capacity. It was also determined that the RCA reached 85% of its total absorption capacity after 30 minutes of soaking; this was used for mixing procedures.
- Modifications to the standard mortar mixing procedure were required for properly mixing mortars containing RCA, including a soaking period of 30 minutes for all aggregate (including RCA) to ensure proper absorption by dry aggregate and adequate mixing.
- Increased amounts of crushing of the RCA will provide more access to virgin aggregates. RCA with larger relative amounts of reactive virgin aggregate will cause higher expansions than RCA that has lower amounts of reactive virgin aggregate in it.
- Higher replacement levels of reactive RCA resulted in higher expansions, which will likely necessitate higher levels of mitigation.
- The precision statement used in the ASTM C 1260 for multi-laboratory testing is acceptable based on this testing, however the coefficient of variation needs to be modified to apply to RCA.

5 REFERENCES

[1] Meyer, C. (2007): The economics of recycling in the US construction industry. in Sustainable Construction Materials and Technologies. Coventry, United Kingdom: Taylor & Francis Group.

[2] Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., and Foo, S. (2009): New mixture proportioning method for concrete made with coarse recycled concrete aggregate. Journal of Materials in Civil Engineering, 2009. 21(10): p. 601-611.

[3] Shayan, A. and Xu, A. (2003): Performance and properties of structural concrete made with recycled concrete aggregate. ACI Materials Journal, 2003. 100(5): p. 371-380.

[4] Nagataki, S., Gokce, A., Saeki, T., and Hisada, M. (2004): Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. Cement and Concrete Research. 34(6): p. 965-971.

[5] U.S. Dept. of Transportation – Federal Highway Administration (2004): Transportation applications of recycled concrete aggregate. http://www.rmrc.unh.edu/Research/tools/RCAREPORT.pdf Accessed July 31, 2011

[6] Melton, J.S. (2004): Guidance for recycled concrete aggregate use in the highway environment, in ACI SP-219: Recycling concrete and other materials for sustainable development, T.C. Liu and C. Meyer, Editors. American Concrete Institute: Farmington Hills, Mich. p. 47-60.

[7] Scott, H.C., IV and Gress, D.L. (2004): Mitigating alkali silica reaction in recycled concrete, in ACI SP-219: Recycling concrete and other materials for sustainable development, T.C. Liu and C. Meyer, Editors.American Concrete Institute: Farmington Hills, Mich. p. 61-76.

[8] Shehata, M.H., Christidis, C, Mikhaiel, W., Rogers, C., and Lachemi, M. (2010): Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction. Cement and Concrete Research. 40(4): p. 575-582.

[9] Fournier, B. and Malhotra, V.M. (1996): Reducing expansion due to alkali-silica reactivity, in Concrete International. American Concrete Institute. p. 55-59.

[10] ASTM C 1260: Standard test method for potential alkali reactivity of aggregates (mortar-bar method), in ASTM C 1260, ASTM International, Editor. 2007, ASTM International: West Conshohocken, PA. p. 5.

[11] ASTM C 305: Standard practice for mechanical mixing of hydraulic cement pastes and mortars of plastic consistency, in ASTM C 305, ASTM International, Editor. 2006, ASTM International: West Conshocken, PA.

[12] Lu, D., Fournier, B., and Grattan-Bellew, P.E. (2006): Effect of aggregate particle size on determining alkali-silica reactivity by accelerated tests. Journal of ASTM International. 3(9).

Table 1: RCA Exposure Block Source Information

Reactive Virgin Aggregate by Quarry	Mineralogy	AMBT 14 Day Expansion (%)	Concrete Prism Test 1-Year Expansion (%)	Reactivity Level According to CPT	Expansion / Extent of Damage in Exposure Block	Exposure Site Location
Alberta	Mixed mineralogy gravel (CA)	0.36	0.09	Moderately reactive	0.15-0.25% expansion	Ottawa, ON Canada
Bernier	Argillaceous Limestone (CA)	0.17	0.07	Highly reactive	0.15 – 0.25% expansion	Ottawa, ON Canada
Potsdam	Sandstone (CA)	0.09	0.13	Highly reactive	0.15-0.25% expansion	Ottawa, ON Canada
Springhill	Greywacke (CA)	0.46	0.22	Very highly reactive	0.15-0.25% expansion	Ottawa, ON Canada

Table 2: Cement Oxide Analysis

Oxide	Oxide Short	CANMET Cement
Silicon Dioxide	SiO_2	19.57
Aluminum Oxide	Al_2O_3	4.88
Iron Oxide	Fe_2O_3	2.91
Total (SiO_2 + Al_2O_3 + Fe_2O_3)		27.36
Calcium Oxide	CaO	60.82
Magnesium Oxide	MgO	2.52
Sodium Oxide	Na_2O	0.27
Potassium Oxide	K_2O	0.97
Total Alkalies	Na_2O	0.91
Sulfur Trioxide	SO_3	3.32
Loss on Ignition		2.82

Table 3: Aggregate Gradation Requirements for AMBT

	Aggregate Gradation					
	2.5 mm - 5.0 mm	2.36 mm-4.75 mm	1.18 mm - 2.36 mm	600 µm - 1.18 mm	300 µm - 600 µm	150 µm - 300 µm
ASTM C 1260 - Accelerated Mortar Bar Test (AMBT)	0%	10%	25%	25%	25%	15%

Table 4: Multi-laboratory AMBT Bar Sets (Each Set Composed of 3 Bars)

Number of Specimen Sets Cast by Each Laboratory Using Re-crushed Fines				
Mixture Type	Potsdam	Springhill	Bernier	Alberta
100% RCA	1	2+1	1	1
50% RCA	1	1	2	2
25% RCA	1	1	1	2
Number of Specimen Sets Cast by Each Laboratory Using Crusher's Fines				
Mixture Type	Potsdam	Springhill	Bernier	Alberta
100% RCA	1	2	1	1
50% RCA	1	1	2	2
25% RCA	1	1	1	2

Table 5: Average Expansions, Coefficient of Variations, and Precision Limits and Outliers for Re-Crushed RCA

RCA Replacement Level and Aggregate Type	Number of Samples (Bars)	Average Expansion (%)	Coefficient of Variation (%)	Precision Boundary Limits (43% Above or Below Mean Expansion)		
				Lower Expansion Boundary (%)	Upper Expansion Boundary (%)	Number of Outliers
25% Alberta	24	0.20	11.5	0.12	0.29	0
50% Alberta	24	0.28	11.5	0.16	0.40	0
100% Alberta	12	0.31	5.8	0.18	0.45	0
25% Bernier	12	0.08	22.8	0.04	0.11	0
50% Bernier	24	0.09	8.5	0.05	0.13	0
100% Bernier	12	0.11	17.5	0.06	0.16	0
25% Potsdam	12	0.05	27.5	0.03	0.07	0
50% Potsdam	12	0.06	7.3	0.04	0.09	0
100% Potsdam	12	0.07	10.4	0.04	0.10	0
25% Springhill	12	0.20	16.5	0.11	0.28	0
50% Springhill	12	0.29	7.9	0.16	0.41	0
100% Springhill	36	0.32	20.2	0.18	0.46	0

Table 6: Expansion Averages, Coefficient of Variations, and Precision Limits and Outliers for Crusher's Fines RCA

RCA Replacement Level and Aggregate Type	Number of Samples (Bars)	Average Expansion (%)	Coefficient of Variation (%)	Precision Boundary Limits (43% Above or Below Mean Expansion)		
				Lower Expansion Boundary (%)	Upper Expansion Boundary (%)	Number of Outliers
25% Alberta	24	0.10	19.0	0.06	0.15	0
50% Alberta	24	0.14	27.6	0.08	0.20	1
100% Alberta	12	0.15	21.1	0.09	0.21	0
25% Bernier	12	0.07	20.5	0.04	0.10	0
50% Bernier	24	0.06	21.0	0.03	0.08	0
100% Bernier	12	0.08	16.9	0.04	0.11	0
25% Potsdam	12	0.06	22.9	0.04	0.09	0
50% Potsdam	12	0.07	13.1	0.04	0.10	0
100% Potsdam	12	0.08	10.8	0.04	0.11	0
25% Springhill	12	0.08	22.2	0.05	0.11	0
50% Springhill	12	0.11	27.1	0.07	0.16	0
100% Springhill	24	0.09	26.8	0.05	0.12	0

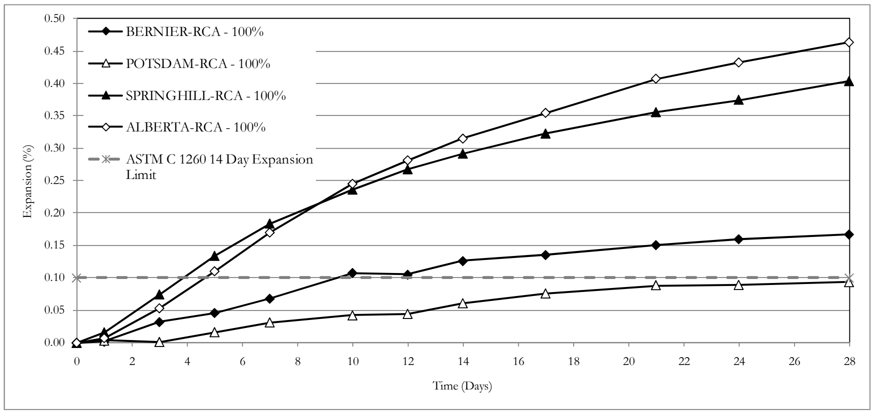

Figure 1: Expansion as a Function of Time for 100% Replacement RCA for Re-Crushed Aggregate (Oregon State University Laboratory Specimens Only)

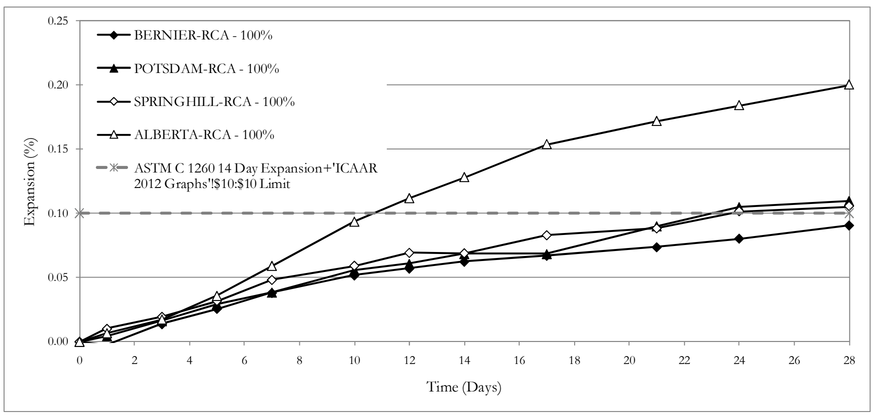

Figure 2: Expansion as a Function of Time for 100% Replacement RCA for Crusher's Fines Aggregates (Oregon State University Laboratory Specimens Only)

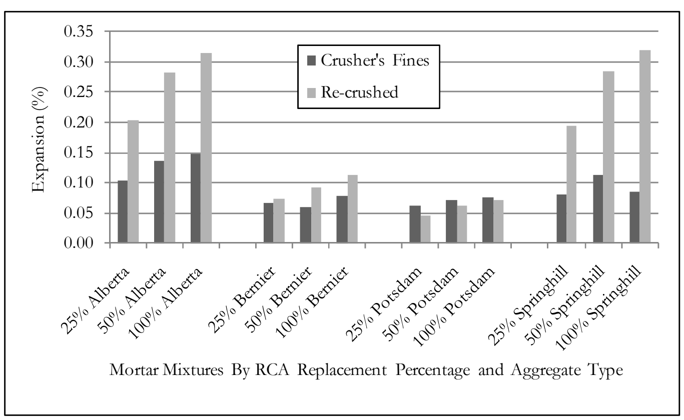

Figure 3: Average Expansion at 14 Days for all Re-crushed and Crusher's Fines RCA at Various Replacement Proportions