AN ABSTRACT OF THE THESIS OF

Matthew P. Adams for the degree of Master of Science in Civil Engineering presented on January 9, 2012

Title: Alkali-Silica Reaction in Concrete Containing Recycled Concrete Aggregates

Abstract approved:

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Jason H. Ideker

Using recycled concrete aggregate (RCA) as a replacement for natural aggregate in new concrete is a promising way to increase the overall sustainability of new concrete. This has been hindered, however, by a general perception that RCA is a sub-standard material due to the lack of technical guidance, specifically related to long-term durability, on incorporating RCA into new concrete. The goal of this research project was to determine whether current testing methods could be used to assess the potential alkali-silica reactivity of concrete incorporating RCA. The test methods investigated were ASTM C1260 and ASTM C1567 for assessing natural aggregate susceptibility to alkali-silica reactivity (ASR), and the ability of supplementary cementitious materials (SCMs) to mitigate ASR, respectively.. Seven different RCA sources were investigated. It was determined that ASTM C1260 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 to evaluate repeatability and consistency of results. The authors recommend modification to the mixing and aggregate preparation procedures, when testing the reactivity of RCA using ASTM C 1260.

This study also investigated the efficacy of replacing portland cement with supplementary cementitious materials (SCMs), known to mitigate alkali-silica reaction (ASR) in concrete with virgin aggregates, to control ASR in concrete incorporating reactive RCA. The SCMs investigated as part of this study included: fly ash (class F), silica fume, and metakaolin. The results of modified alkali-silica reactivity tests, ASTM C1260 and ASTM C1567 (AMBT), are presented for two different recycled concrete aggregates when using 100% portland cement, binary blends of portland cement and fly ash, and ternary blends of portland cement, fly ash and metakaolin or silica fume. The results indicate that SCMs can effectively mitigate ASR in concrete made with RCA. A 40% replacement of portland cement with class F fly ash was able to reduce expansions to below 0.10% in the AMBT for concrete containing 100% of a highly reactive recycled concrete aggregate. A ternary blend, however, of portland cement with a class F fly ash and metakaolin was most effective for both RCAs tested in this study. Higher levels of mitigation may be required for some RCAs, compared to the level required to mitigate ASR in concrete made with their original natural aggregates, depending on the age and composition of the RCA.

Alkali-Silica Reaction in Concrete Containing Recycled Concrete Aggregates

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes the release of my thesis to any reader upon request.

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Matthew P. Adams, Author

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1. General Introduction

1.1   Scope and Layout of This Thesis

This thesis follows the manuscript option for the Masters of Science Thesis in the Oregon State University Graduate School Thesis Guide 2011-2012. The thesis contains a study on the applicability of standard test methods to detect potential alkali-silica reactivity (ASR) of recycled concrete aggregates (RCA). ASR is one of the most prevalent causes of concrete deterioration worldwide; it can cause significant cracking and reduces the service life of concrete structures and pavements. The study reported on in this thesis was performed by casting mortar bars with varying levels of RCA used as a replacement for natural aggregate. The mortar bars were subjected to accelerated aging conditions according to applicable ASTM standards and the expansion of the bars (an indicator of the reaction development) was monitored. In addition, mitigation options to control ASR were also investigated using the same techniques. Two technical papers containing original research were developed to report on the findings of these studies. These publications provide missing information in the literature concerning the long-term durability of recycled concrete aggregates, evaluated through accelerated laboratory testing, and provide verification and modification of existing test methods to evaluate mitigation of alkali-silica reactivity in concrete made with reactive recycled concrete aggregates. The thesis is outlined as follows:

Chapter 1: *General Introduction* – This chapter provides a basic introduction to recycled concrete aggregates and the mechanical properties and durability of concrete made with recycled concrete aggregates. Special consideration is paid to the alkali-silica reactivity of recycled concrete aggregates. An overview of alkali-silica reaction is also provided, as well as current test methods to detect ASR, and ASR mitigation techniques.

Chapter 2: *Manuscript 1* – The title of the first technical paper presented in this thesis is "Applicability of the ASTM C1260 Accelerated Mortar Bar Test for Alkali-Silica Reactivity Testing of Recycled Concrete Aggregates." This manuscript evaluates the applicability of the ASTM C1260 test for use with recycled concrete aggregates. This is accomplished through a review of the reactivity of seven different aggregates that were examined as part of a multi-laboratory study conducted at four different university laboratories. Expansions of mortar bars containing RCA are presented, along with the multi-laboratory coefficients of variation

and precision. Recommendations for modifications to the ASTM C1260 test are presented. Additional data collected for this paper are presented in Appendix A. This manuscript will be submitted to the Journal of ASTM International.

Chapter 3: *Manuscript 2* – The second technical paper presented in this thesis is entitled "Using Supplementary Cementitious Materials to Mitigate Alkali-Silica Reaction in Mortar Bars Made with Recycled Concrete Aggregate." In this paper, the efficacy of supplementary cementitious materials to prevent alkalki-silica reaction is examined in mortar made using recycled concrete aggregate. Expansions of mortar bars created with two different RCAs are examined when blends of portland cement and class F fly ash, silica fume, and metakaolin are used to reduce ASR. The test method described in ASTM standard C1567 was used as part of this study. This manuscript will be submitted to the American Concrete Institute's Materials Journal.

Chapter 4: *General Conclusion* – This chapter summarizes the goals and findings of this research and provides conclusions tying the research from both manuscripts together. Future work based on this research is also discussed.

1.2   Background and Introduction

Recycled concrete aggregate is reported to have first been used in Europe after World War II as part of the rebuilding and cleanup effort throughout the continent [1, 2]. However, this did not result in significant continuation of use, or even an increase in use of RCA worldwide. More recently, however, as sustainable construction practices have gained popularity, and the public has demanded environmental responsibility, interest in using the material has increased. A recent executive order from President Barack Obama stated that by 2015, 15 percent of construction and demolition debris must be diverted from landfills and recycled [3]. This call has been echoed through-out Canada and Europe, but without sufficient technical guidance, use of RCA has not gained popularity [4].

About 3 million tons of RCA is produced annually by natural aggregate producers, contractors, and recycling facilities [5]. RCA is typically used as road sub-base, but can also be used as aggregates in recycled concrete aggregate concrete (RCAC), hot mix asphalt

(HMA), riprap, or fill. Figure 1-1 shows the use of RCA as a percentage of all RCA produced [6].
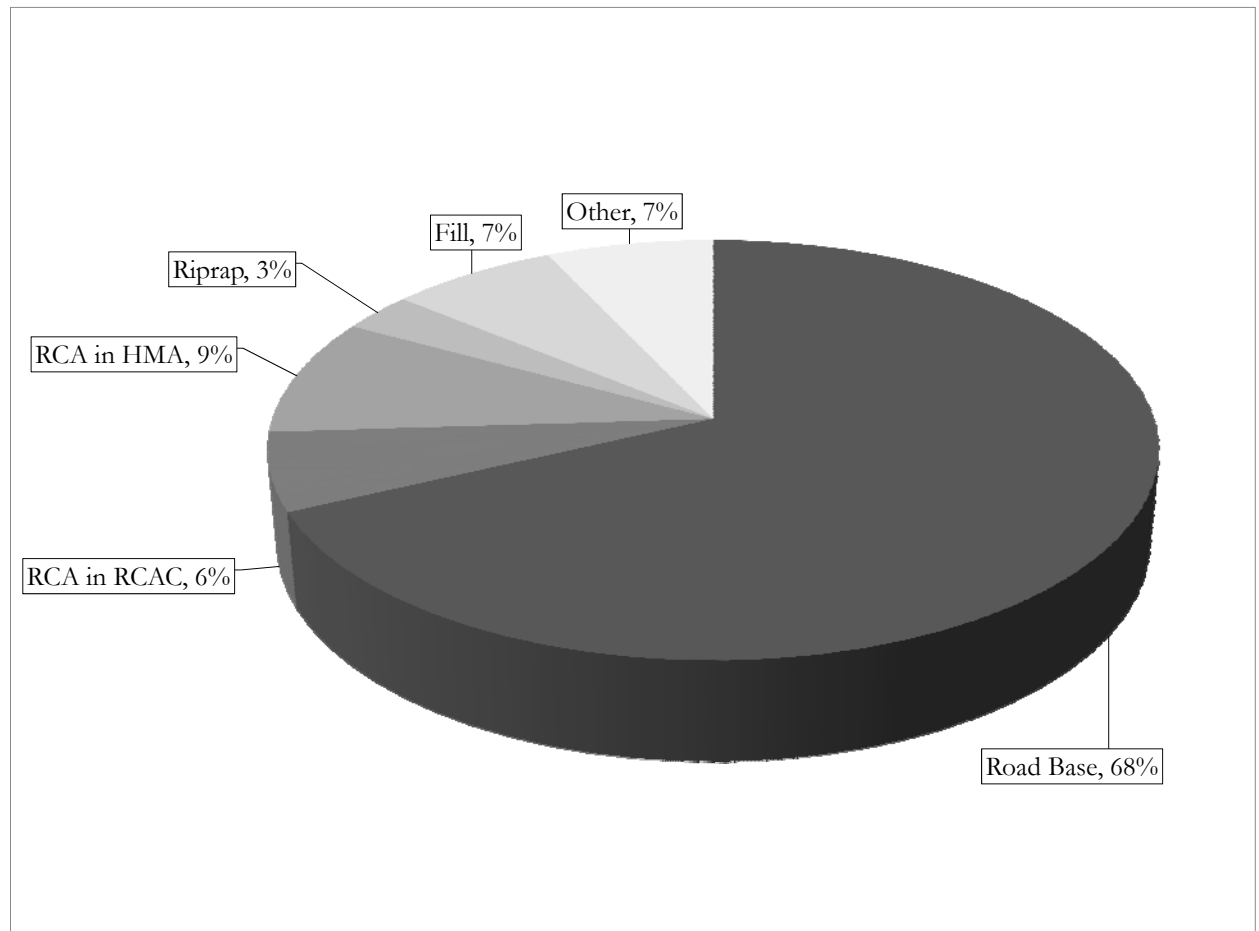
Figure 1-1: Use of RCA [6]

A 2003 survey by the Federal Highway Administration (FHWA) provides an overview of how RCA has been used within the United States. This survey reported that 41 states recycled concrete debris as aggregates, of those 41 states 38 used RCA as base material and 17 used it as miscellaneous aggregate. Only 11 states, however, reported the use of RCA in new concrete [7]. Five states: Texas, Michigan, Minnesota, California and Virginia, were selected for an in-depth review as part of this study. One of the most prevalent reasons given by this group of states for not using more RCA in new concrete was the general consideration that it was a substandard material by both the public and designers. They cited the need for more technical guidance and acceptance into building codes as a way to educate

engineers on the use of RCA and increase its use [7]. This line of reasoning was echoed in a study by Melton, who also stated that contractors, government officials, and the general public did not want to use RCA because they felt landfilling construction and demolition waste was acceptable [8]. Not only is more technical guidance needed on using RCA as a replacement for natural aggregates in concrete, but research into recycled concrete aggregate concrete has focused mainly on mechanical properties of the material, with less focus given to the long-term durability. The work that has studied RCAC durability has focused mainly on freeze/thaw and shrinkage. Other durability issues, such as carbonation, sulfate attack, and ASR have been studied, albeit only minorly and merit more research in the future. This review covers both the mechanical and long-term durability properties of recycled concrete aggregate concrete. Special attention is focused on alkali-silica reaction (ASR) and the potential for RCA to cause ASR in new concrete.

Terminology Notes

Recycled concrete aggregate (RCA) is an aggregate made from the recovery of demolished concrete. This material can be either a coarse aggregate or a fine aggregate. Natural aggregates (NA) are aggregates that have not previously been used. Throughout this thesis, mixtures of concrete made with varying levels of RCA as a replacement for NA will be referred to recycled concrete aggregate concrete (RCAC) and concrete made with 100% natural aggregates will be referred to as natural aggregate concrete (NAC).

1.2.1   Sustainability of Recycled Concrete Aggregate

In the United States, the construction and demolition waste stream is about 250-300 million tons a year (2002 numbers) [9] which makes up about 50% of the total U.S. waste stream [10]. Sixty percent of this, or 150-180 million tons, of construction and demolition debris is concrete [11]. It is recognized that this number needs to be reduced, and one of the viable options open to the construction industry is to divert RCA from the waste stream, and use it as aggregate. RCA is currently already used as road sub base material, and in some places, such as Belgium, the market for increasing the use of RCA as sub base is scarce due to the already dense infrastructure which is focused mainly on maintenance, not replacement [4]. A different market that is open for use of RCA is as a replacement for NA in concrete.

Increasing the use of RCA can have several benefits with respect to sustainable construction. It can (1) reduce the amount of debris sent to landfills, (2) decrease the amount of natural aggregates mined from the earth, and (3) reduce the amount of transportation required to transport aggregates.

Reducing the amount of debris sent to landfills is desirable from both an economic and environmental point of view. The cost to dispose of construction and demolition waste into a landfill is about $50 a cubic yard in the U.S. [11], this amount can be reduced, however, by diverting the debris to recycling efforts. Reducing the amount of materials sent to landfills can also help to reduce greenhouse gases, and reduce the need to open new landfills on unused land [12]. Many locations around the world are working to discourage the use of landfills and increase recycling by steadily increasing the cost of disposing waste in the landfills [10].

Decreasing the amount of aggregates mined from the earth is important because, as society continues to construct and build up our urban environments, locally available sources of aggregate near these environments are depleted. This can have an effect on the overall transportation costs of aggregates, as well as increase the amount of greenhouse gases produced transporting them from further distances [13].

Using RCA can significantly reduce the transportation required to bring aggregates to concrete facilities, particularly in urban districts. Many RCA sources come from demolition sites within urban districts, and are processed at facilities in urban districts, which can then be sent to concrete facilities in those same urban districts. If natural aggregates need to be shipped from a large distance away from the facility due to the extent of the urban boundaries, the transportation can have large effects on the overall sustainability of concrete due to the greenhouse gases produced from transportation. Using the RCA reduces these greenhouse gases, while also reducing the cost to ship the aggregates to the concrete facilities [10].

A life cycle analysis (LCA) on the use of recycled concrete aggregate was performed by Marinkovic et al. considering the construction of a building in Belgrade, Serbia. The results of this LCA actually showed that using RCA would be less beneficial for this particular

project [14]. The main reason cited for this was the difference in transportation. It was assumed that RCA would have to be trucked in to the concrete facility, whereas the NA could be shipped via barge up a river. The barge was much more environmentally friendly and more cost effective which made the NA a better choice [14]. The results of this study show, however, how large the impact of transportation is on the environmental viability of RCA. Conversely, a study by Christiansen, showed that during the construction of the Kern Center in Milwaukee, WI, recycling of the waste produced during construction would have saved the project almost $20,000. And even though the amount of concrete that could have been recycled during construction was a small portion, it constituted the second largest cost savings when recycled out of all the construction materials reviewed [15].

Beyond these reasons using RCA can help to meet sustainability requirements of green building rating systems. LEED, or Leadership in Energy and Environmental Design, which is a rating system developed by the U.S. Green Building Council, uses a credit system to rate a building's sustainability from certified, to silver, gold and platinum [16]. RCA can be used to achieve several credits under this rating index: Credits 2.1 and 2.2 for recycling of construction waste, credits 4.1 and 4.2 for using recycled content on the construction project, and credits 5.1 and 5.2 for using local and regional materials [17]. Additionally, RCA can also be used to achieve status as a Living Building under the International Living Future Institute's rating system that gives a structure status as a Living Building if it can achieve a set of 7 goals referred to as 'petals'. RCA can help to achieve the materials petal which seeks to increase the use of properly and locally sourced building materials [18].

Sustainability is an important factor for using RCA, however it has shown that being sustainable can also, depending on conditions of the project, produce a more economical product. Further research and technical guidance on using RCA will only increase its use and availability. This will make the material more attractive in the future, and should continue the trend of incorporating sustainable materials in construction.

1.2.2   General Properties and Characterization of Recycled Concrete Aggregates

Recycled concrete aggregate is produced by crushing demolished concrete, generally from varying sources, into the appropriate gradation for use in civil engineering applications. A

recycled concrete aggregate consists of two phases: the original natural aggregate (ONA) and the adhered mortar (AM) [19]. The ONA was the aggregate used in the parent concrete of the RCA; the AM is comprised of fine aggregate and cement paste. RCA is generally angular in shape because of the crushing required to make it the proper size for use as an aggregate. The AM also results in the RCA being more porous than natural aggregates [20, 21]. Gomez-Soberon observed that the increased porosity of the aggregate caused an increase in the porosity of concrete made with RCA by 3.8% compared to NAC when measured 90 days after casting [22]. A sample of RCA can be seen in Figure 1-1.

Figure 1-2: Recycled concrete aggregate

RCA is produced through a series of crushing operations. Large concrete elements (slabs or building components) are broken up with mobile impact units, which typically also include hooks or some other system to remove reinforcement steel during this initial crushing phase. This rubble is then broken down further on-site to a size that is manageable for transportation to a large scale crushing facility, typically 12-16 in. (30.5 – 40.6 cm) diameter pieces. At the crushing facility this rubble is then crushed further down to a gradation range

of 0.0029 – 1 in. (0.073 – 25 mm). At this phase, a magnet can be passed over the aggregate to remove any remaining reinforcement steel in the concrete [23]. Müeller and Winkler showed that the adhered mortar/cement paste content of an RCA particle increases as the particle size decreases [24]. This was supported in a study by Nagataki et al. that showed that during crushing, the friable portions of the aggregate become loosened first; these generally consisted of the weaker paste areas or aggregates that were cracked prior to crushing [25]. Thus, the AM, which will break off of the ONA before the ONA splits into smaller particles, will constitute a larger portion of the smaller particle sizes.

Absorption Capacity

The absorption capacity of RCA has been shown to be higher than that of NA. Coarse RCA can vary from 2-10% absorption capacity [1, 20-22, 26-31] and between 3-8% for fine RCA [1, 20-22, 28]. Normal weight natural aggregates typically have an absorption capacity of about 1-2% for both coarse and fine aggregates [32]. The increase in absorption capacity of RCA when compared to NA can be attributed to the adhered mortar content of the RCA. The AM causes the RCA to be more porous than natural aggregates, which leads to the higher absorption capacity. Research by Ramamurthy [29] and de Juan and Gutierrez [33], confirmed this when they showed that an increase in absorption capacity of RCA correlated with an increase in the adhered mortar content of the aggregate.

In the United States, the typical tests for classifying the absorption capacity of aggregates are ASTM C127: Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate and ASTM C128: Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate for coarse and fine aggregate, respectively. The manner in which absorption capacity is measured is similar in each test:

1. A sample of aggregate is taken (coarse and fine are done separately);
2. the sample is immersed in water for 24 $\pm$ 4 hours at room temperature;
3. the excess water is decanted from the sample;
4. the sample is brought to a saturated surface dry condition (SSD) either by rolling the aggregates in a towel until excess water is removed (coarse aggregates) or by

drying slowly with a current of air until the aggregates is indicated to be at SSD by the provisional cone test (fine aggregates);
5. the sample is weighed at SSD condition;
6. the sample is placed in an oven at a temperature of 110 ± 5 °C until it dries and the mass reads constant;
7. the sample is then weighed again at oven dry (OD) condition.

The absorption capacity is then determined by the following equation:

$$AC = 100[(S - A) / A]$$

<div align="right">**Equation 1-1**</div>

Where[34, 35]:

AC = the absorption capacity of the aggregate, in %;
S = the mass of the specimen at SSD state, in g or lbs; and
A = the mass of the specimen at OD state, in g or lbs.

Research by Chan et al. has noted a possible problem with the reliability of this test: namely that the presence of AM in the RCA may require a longer soaking time to reach full saturation of the pores in a RCA [26]. Therefore, when determining the AC of RCA, it is recommended that the time to full saturation of the RCA sample is determined, and that is used as the soak time in the AC test.

Soundness

Soundness testing of aggregates estimates the weathering resistance (typically for freeze/thaw resistance) by testing their resistance to repeated immersion in a sulfate solution followed by oven drying. The original mass and then mass after the test are taken and compared to determine the soundness of the aggregate. In the United States, the test standard typically used to perform this test is ASTM C88: Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate [36]. As of 1986, according to Hansen, soundness testing was being completed on RCA using this test method. The results were inconclusive, though, showing mass losses from 0.9 to 58.9 % [37]. Further research by Abbas et al. [38] and Gokce et al. [39] showed that this test was not suitable because the sulfate solution submersion caused a chemical attack that broke the bond of the adhered mortar to the original natural aggregate causing it to break away from the aggregate into small pieces that were washed away. Because of this chemical attack that

breaks the bond between the adhered mortar and the original natural aggregates, the test is too severe and does not give an accurate picture of soundness. Therefore it is not recommended that soundness testing be performed on RCA. Another test method should be developed for assessing the weathering resistance of RCA. It should be noted that the ASTM C88 test is a surrogate test for freeze/thaw resistance, but it is only tested on aggregates, and in fact may not be suitable for use assessing the freeze/thaw resistance of natural aggregates either. Test results have exhibited poor correlation with field performance, and high interlaboratory variability has been observed between tests [32]. The use of ASTM C666: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing may be more appropriate as it tests the entire concrete system, not just the aggregate fraction [40].

Specific Gravity

The typical specific gravity of normal weight natural aggregates is in the range of 2.5 – 2.8 [32]. Observations have shown that the specific gravity of RCA can be significantly lower, and have been in the range of 2.1 – 2.5 [1, 21, 39, 41-43]. The lower density of the RCA compared to the NA is because the density of the AM is lower than that of NA. RCA has varying proportions that are made of AM, and thus the density of the RCA is typically lower than NA [37]. This will also vary based on the source of RCA, e.g. if a lightweight RCA is utilized the observed specific gravity may be even lower than the numbers cited above.

Reactivation of Unhydrated Cement in Recycled Concrete Aggregates

Investigations into long-term mechanical properties of RCAC performed by Kou et al. compared a NAC and an RCAC with a 100% RCA replacement level. It was observed that the compressive strength gain of RCAC over 5 years of curing produced a 62% increase in compressive strength compared to only a 34% increase in compressive strength of NAC. A 65% splitting tensile strength increase in RCAC over 5 years was also reported, compared to only a 37% increase in NAC [43]. The values presented by Kou et al. can be seen in Table 1-1.

Table 1-1: Long-term mechanical properties as presented in Kou et al. [43]

Mechanical property	Mixture type	28 days psi (MPa)	5 years psi (MPa)	Gain from 28 days to 5 years (%)
Compressive Strength	NAC	6350 (43.8)	8540 (58.9)	34
	RCAC	4970 (34.3)	8040 (55.4)	62
Splitting Tensile Strength	NAC	350 (2.43)	480 (3.32)	37
	RCAC	320 (2.26)	530 (3.64)	65

This increase in strength was attributed to the possible long-term hydration of unhydrated cement in the RCA [43]. Other research however shows that this is unlikely, as it was demonstrated that RCA, when finely ground, will not set and harden when put into contact with water, even when cured at high temperatures for prolonged periods [37, 44].

Leaching

RCA is typically stored in stockpiles which are exposed to the elements. As rainwater washes through the stockpiled aggregates, it will run off and enter local eco-systems. The water runoff may cause the leaching of heavy metals from the concrete into the environment. Research by Müeller and Winkler has shown that the heavy metals leached from RCA are extremely low, and meet typical leaching environmental standards [24]. However, due to the fact that RCA is a very inconsistent product because the parent concrete can be made from a large variety of NA, cements, supplementary cementitious materials, and admixtures, leaching characteristics of each source of RCA should be tested to ensure that local environments are protected.

Impurities

Impurities can impair the hardened properties of RCAC significantly [37, 42, 45]. There are a large range of impurities that could be found in RCA that are generally introduced as a part

of the demolition and recycling process: plaster, soil, wood, gypsum, asphalt, paint, metals, glass, masonry, cloth, paper, plastics and chlorides [23, 37].

Kikuchi et al prepared concrete with some of these impurities and showed that the compressive strength and modulus of elasticity were reduced by the inclusion of impurities. This was especially present in concrete containing gypsum, asphalt, and wood chips [42]. The American Concrete Institute's report: "Removal and Reuse of Hardened Concrete" states all contaminants should be removed from RCA prior to using them in new concrete, even if this means further processing is required after crushing [23].

Contamination by chlorides is also of significant concern. Chlorides can penetrate parent concretes during their service life through the application of deicing salts or the presence of marine environments. Chlorides can also be introduced in the parent concrete by the natural aggregates and admixtures [37]. Debieb et al. showed that RCAC made with RCA that had between 3-4.6% chloride content by cement weight had a probability of 90% that corrosion of the steel in concrete made with that RCA [45]. This was determined through performing ASTM C876: Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete [46]. This test method measures the electrical corrosion potential of uncoated reinforcing steel in concrete. The criteria for this standard state that if potentials over an area are more negative than -0.35 V then there is a 90% chance that the reinforcing steel is corroding. Debieb et al. observed an electric potential of -0.57 V in the RCAC containing RCA that had chloride contamination [45]. Hansen showed that concrete in various conditions was found with up to 7.5% chloride content by mass of cement [37]. The American Concrete Institute's *Guide to Durable Concrete* suggests that chloride contents (for water soluble chlorides be below 0.06%, 0.08%, or 0.15% by mass of cement for prestressed concrete, reinforced concrete in wet conditions, or reinforced concrete in dry or protected conditions, respectively [47]. Therefore it is recommended that RCAs be screened for chloride contamination prior to their being used in RCAC. Research still needs to be completed, however, to see if typical concrete standards restricting the content of chlorides in NA can be applied to RCA.

1.2.3   Mechanical Properties of Concrete made with Recycled Concrete Aggregates

Extensive work has been completed on the mechanical properties of concrete made with RCA, especially investigations into the compressive strength and modulus of elasticity. In general, it was found that the mechanical properties of concrete made with RCA are not as high as concrete made with natural aggregates. However, some properties, through a change in mixture design or careful choice of recycled aggregate, were shown to be able to meet or exceed the properties of concrete made with natural aggregate.

Compressive Strength

Generally, RCAC mixtures made using the same mixture design as NAC, where the NA is replaced by RCA on a mass for mass basis will exhibit lower compressive strengths. Reductions in strength were noted to be anywhere from 0% up to 30%; and depended on the amount of RCA used as replacement for NA in the mixture, whether the RCA used was fine or coarse aggregate, and the amount of cement, water content, and w/cm (water to cementitious material ratio) of the mixture [20-22, 28, 30, 42, 48]. The main factor that exacerbated the decrease in compressive strength was the increase in the replacement ratio of recycled concrete aggregate [21, 22, 42, 48-50].

Padmini et al showed that similar compressive strengths could be achieved in RCAC when a lower w/cm was used in the mixture design [51]. The same effect could also be accomplished by increasing the cement content of the mixture [30]. Mandal et al showed that a 10% replacement of portland cement, by weight, with fly ash in the mixture improved the compressive strength of RCAC to be similar to that of NAC [48].

The moisture state of the RCA also affects the compressive strength of the concrete. Poon et al. showed that aggregates left to air dry before using them in concrete produced compressive strengths higher than that of RCAC made with oven dried or saturated surface dry aggregates [28]. The strength of the original concrete also had an effect on the strength of the RCAC. Stronger parent concrete used as RCA in new concrete resulted in higher compressive strengths [25, 42].

Modulus of Elasticity

The modulus of elasticity of concrete made with RCA has also been extensively studied. Research has shown that the modulus of elasticity of the RCAC is significantly affected by RCA content. The properties of the RCA were shown to have a large effect on the modulus of elasticity. The modulus of elasticity of concrete is controlled, in part, by the density of the aggregate [32, 52]. Due to the presence of adhered mortar, the density of RCA is lower than that of a typical natural aggregate. In general, the modulus of elasticity of RCAC was 5-20% lower when compared to concrete made with NA [20, 42, 49, 51, 53, 54]. Müller showed reductions up to 31% [55] and Katz showed a reduction of 50% [54]. Katz, however, was using a mix design that contained 100% replacement of both fine and coarse NA with RCA, which accounted for the larger reduction in modulus of elasticity. Khatib confirmed that the modulus of elasticity of RCAC decreased as the replacement ratio of RCA to NA increased [49]. Padmini et al also showed that the modulus of elasticity is further reduced as the maximum RCA size is reduced [51]. This was due to the increase in RCA mortar content as the particle size decreased. Thus an RCAC with a smaller maximum size aggregate, with the same total aggregate content would have a greater adhered mortar content when compared to an RCAC with a larger maximum size aggregate.

Tensile and Flexural Strength

Tensile strength was found to be lower for concrete made with RCA when compared to concrete made with just NA [23, 37, 43, 51]. Concrete made with both fine and coarse RCA exhibited even lower tensile strengths than those made solely with coarse RCA [37]. Kou et al. showed, however, that long-term curing of the RCAC improved the tensile and flexural strengths of the concrete, even above that of NAC [43]. Flexural strengths were found to be similar or slightly lower than that of NAC [20, 37, 43, 51].

Shrinkage

Hansen reported an increase in drying shrinkage up to 50% in RCAC over that of NAC [37]. Later research showed that drying shrinkage in concrete containing RCA could more than double over shrinkage observed similar concrete mixes containing only NA [20, 42, 56]. The

increase in drying shrinkage was explained by the increase in the mortar content in concrete containing RCA. The higher paste content of RCAC, which is less dimensionally stable than the ONA contained in the RCA provided less restraint than concrete made with NA [32].

Research showed that the drying shrinkage of RCAC increased as the replacement ratio of RCA to NA increased in the concrete [49, 56]. As described above, this was due to the increasing adhered mortar content that occurs as more RCA is introduced to the mixture. Fine RCA was shown to have more of an effect on the drying shrinkage than coarse RCA [42, 50]. The fine RCA was shown to have higher adhered mortar content than that of coarse aggregates [24, 25]. The increase in drying shrinkage with fine RCA over that of coarse RCA in RCAC was attributed to the increase in adhered mortar.

Creep

Creep in RCAC was found to increase between 24% and 60% when compared to concrete made with NA [20, 37, 53, 56]. Gomez-Soberon [53] and Castano-Tabares et al. [56] both showed that the creep increased as the ratio of replacement of RCA increased in RCAC. Gomez-Soberon also showed that even at a replacement ratio of 15% RCA, the creep was increased by 24% [53]. The increase in creep was explained by the reduced natural aggregate content in RCAC caused by the two-phase RCA particles. Natural aggregates act as a restraint against shrinkage [32], thus the lower NA content in RCAC provides less resistance against deformations in the cement paste.

1.2.4 General Durability of Concrete Made with Recycled Concrete Aggregates

While the durability of RCAC has not been as extensively studied as the mechanical properties, there have been efforts put forth to quantify the long term durability of the material. This section will introduce previous work completed on topics concerning the long-term durability of concrete made with recycled concrete aggregates including: abrasion resistance, carbonation, chloride attack, and corrosion of reinforcement, freeze-thaw resistance, and sulfate exposure. Alkali-silica reaction resistance of RCAC will be presented as part of a more in-depth discussion of alkali-silica reaction in section 1.2.5.

Abrasion Resistance

Abrasion resistance is measured in two different ways, primarily: the Los Angeles abrasion test (tests aggregates) and the abrasion resistance of horizontal concrete surfaces (tests concrete). In the Los Angeles abrasion test the deterioration of aggregates by mass loss measurement is assessed through abrasion, impact, and grinding while they are rolled in a large steel drum containing 6-12 steel ball bearings (depending on gradation of aggregate) [57, 58]. Hansen reported mass loss values between 20-40% loss [37]; de Juan and Gutierrez confirmed the higher end of this spectrum, though they reported a significantly higher lower boundary for abrasion resistance of the aggregate: 37-42% loss [33]. Some concern about the applicability of the Los Angeles abrasion test was put forth by de Juan and Gutierrez, however. The authors showed that it was heavily controlled by adhered mortar content. When the adhered mortar content of the RCA was high, the Los Angeles abrasion test loss percentages were also high. They also observed that, generally, after the test most of the RCA adhered mortar had been ground to powder. They suggested that the test may be too aggressive given the nature of recycled concrete aggregate [33]. No testing provided a correlation of the results of the Los Angeles abrasion test to the abrasion resistance of the horizontal concrete surface when using RCA. Further testing on the abrasion resistance of aggregates should be completed to ascertain the validity of the Los Angeles abrasion test.

An alternate method for testing the abrasion resistance is by measuring the resistance of a concrete surface by subjecting it to an abrasive force for a certain amount of cycles. This test, in the U.S., is covered under ASTM standard C779: Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces [59]. Results reported in literature were inconsistent. Limbachiya et al. reported that abrasion depths of concrete containing RCA were greater than those of NAC, for concrete with either coarse or fine RCA. The abrasion depths, however, did not correlate to the amount of RCA in the mixture. For coarse aggregates, an abrasion depth of 0.032 in (0.81 mm) was reported for a 30% RCA to NA replacement ratio, however when the replacement ratio was raised to 50% the abrasion depth reduced to 0.027 in (0.069 mm), and when the replacement ratio was 100% the abrasion depth fell in between those two values at 0.031 in (0.078 mm). The study did, however, show a positive correlation between the strength and abrasion resistance [50]. Dhir

et al. also completed horizontal abrasion testing on concrete made with recycled concrete aggregate. It was observed that for RCAC containing up to 50% replacement ratio with coarse RCA there was little difference between RCAC and NAC abrasion depths. However, once the replacement ratio was increased to 100% the abrasion depth increased by 34% when compared to that of NAC [21]. Further testing is merited on RCAC concerning its resistance to abrasion. RCA particle dispersion in concrete mixes at various replacement ratios and adhered mortar content may have a large effect on the abrasion resistance of RCAC which could lead to the varying results presented here. More research will help to elucidate whether RCA has a significant impact on the abrasion resistance of concrete and what steps can be taken to modify the abrasion resistance of the concrete incorporating RCAC if it is in fact more pronounced than NAC.

Carbonation, Chloride Penetreation, and Reinforcement Corrosion

Reinforcing steel, when cast in concrete, typically forms an iron oxide protection owing to the high concentration of (OH^-) ions provided by the high alkalinity in the concrete (pH typically above 12.5). Carbonation of concrete causes a decrease in the alkalinity of the pore solution, and thus a decrease in the pH of the concrete. When the pH decreases below 11.5, the protective passive iron oxide layer on the reinforcement steel begins to be destroyed, and corrosion can occur. Because of this, the carbonation depth is a good indicator of the possibility of reinforcement corrosion in concrete [32, 52]. Carbonation depth results vary widely among published material. A summary of the testing results on carbonation can be seen in Table 1-2 [21, 30, 37, 42, 50, 60, 61]. A "-" indicates worse performance when compared to NAC and a "+" indicates better performance when compared to NAC. "N.R." means that the item was not reported for this particular test.

Table 1-2: Summary of effect of RCA content on carbonation in concrete

Effect on Carbonation Depth When Compared to NAC	Carbon Dioxide Content in Air (%)	Temperature (°C)	Relative Humidty (%)	RCA Size	RCA Replacement Ratio (%)	Reference
----	20	20	60	Coarse	N.R.	Hansen
negligible	5	30	60	Coarse	N.R.	Kikuchi et al.
-	5	30	60	Fine	N.R.	Kikuchi et al.
negligible	4	N.R.	N.R.	Coarse	< 50	Dhir et al.
-	4	N.R.	N.R.	Coarse	>50	Dhir et al.
-	N.R	N.R.	N.R.	Coarse	100%	Sagoe-Crentsil et al.
+	5	20	50	Coarse	20%	Levy and Helene
++	5	20	50	Coarse	50	Levy and Helene
negligible	4	20	55	Coarse	30	Limbachiya et al.
+	4	20	55	Coarse	50	Limbachiya et al.
++	4	20	55	Coarse	100	Limbachiya et al.
+	4	20	55	Fine	20	Limbachiya et al.
++	4	20	55	Fine	50	Limbachiya et al.
-	10	40	70	Coarse	100	Otsuki et al.

As can be seen, the level of carbon dioxide used in the carbonation test plays an important role in the in the overall carbonation depth of the concrete. The 10% carbon dioxide and 20% carbon dioxide tests both present increased carbonation depths when RCA was incorporated into the mixture. Comparing the results of Kikuchi et al. [42] and Limbachiya et al. [21] there is also disagreement between studies as to whether fine RCA causes worse or better carbonation depths in RCAC. When examining the effect of replacement ratio on carbonation depths Limbachiya et al. [50] and Levy and Helene [60] show that increased replacement ratios of RCA to NA decrease the carbonation depth in RCAC whereas Dhir et al. [21] directly contradicts this. Limbachiya et al. observed that the an increased concrete strength will decrease the carbonation depth in concretes with RCA [50]. This was

confirmed by Otsuki et al. who observed that the carbonation depth increases as the water to binder ratio increases [61].

It is evident from the variation in testing standards and results that are reported in literature that more testing needs to be completed on RCAC to determine typical carbonation depths of the material. Rao et al. reported that the increase in carbonation depth may be due to the adhered mortar on the RCA [5]. The inherent variability in the amount of adhered mortar between RCA sources could also be causing such large variations in the results of the carbonation tests. More testing should be completed and an attempt to correlate the results to several factors including strength, replacement ratio, and adhered mortar content should be performed to see if carbonation testing can be performed on RCA.

Chloride permeability can also be used to determine the probability that reinforcing steel will corrode in concrete. The protective oxide layer surrounding the reinforcing steel in concrete can be destroyed in the presence of chloride ions, even in pH levels above 11.5. Therefore chloride penetration can increase the probability of steel corrosion. Chloride penetration has been shown to increase in concrete created with RCA, although not significantly [61]. Further research into the chloride permeability of RCAC is merited; and care should be used when incorporating RCA in an environment where chlorides will be present until more is known about chloride permeability of RCAC that the probability of steel reinforcement corrosion is not increased. Furthermore, proper analysis of the RCA particles themselves should be made prior to use in concrete because chloride content in the RCA can increase the chances of corrosion in reinforcing steel significantly [45].

Freeze-Thaw Resistance

Freeze-thaw resistance of concrete made with recycled concrete aggregates has been extensively studied. Freeze-thaw deterioration is marked by cracking, spalling, exudation, and even scaling concrete surfaces. As ice forms within the pores in the hardened concrete matrix it swells. This swelling compresses unfrozen water and causes pressures within the pores of the concrete to increase, and can only be relieved if the water can move to unfrozen pores. If the water cannot escape to surrounding pores, due to either the adjacent pores being too far, or nonexistent, the compressed water will cause the pore to expand, imparting

pressures on the surrounding paste. If these pressures exceed the tensile strength of the concrete, deterioration can occur. This phenomenon can also occur in saturated aggregates within the concrete [32]. Freeze-thaw can be controlled by introducing air voids to the mixture creating well spaced voids of proper size into the concrete using an air-entraining admixture. These voids allow the water to expand as it freezes without causing stress in the smaller pores [13]. Resistance to freeze-thaw action is tested by subjecting concrete prisms to a series of freezing and thawing cycles while the concrete is surrounded by water. Damage is then typically measured by determining the change in the dynamic modulus of elasticity and the mass loss of prisms. In the U.S., two test standards are commonly used to do this testing:

- ASTM C666: Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing [40]; and
- AASHTO T161: Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing [62]

A typical freeze/thaw chamber in which these tests are performed can be seen in Figure 1-3.

Figure 1-3: Freeze/thaw chamber

Reports on the freeze-thaw susceptibility of concrete have shown that the RCAC has a similar resistance to freeze-thaw action when compared to NAC [1, 21, 50, 63]. Some tests, however, showed that RCAC had a much lower resistance to freeze-thaw deterioration than NAC, even though they were air entrained; however, no information was given on the air content of the parent concrete for these mixtures [37, 42]. Gokce et al. determined, however, that the air entrainment of the original concrete plays a significant role in the freeze-thaw resistance of RCAC. Even small amounts of non-air entrained RCA were able to cause a significant decrease in the freeze-thaw resistance of the concrete [63]. These studies show that it is important to incorporate RCA that comes from parent concrete that was properly air entrained, and that proper air entraining of RCAC can provide suitable freeze/thaw resistance in RCAC.

Sulfate Exposure

Sulfate attack in concrete causes chemical reactions that typically lead to the formation of ettringite within the concrete matrix. This later formation of ettringite causes expansion in the concrete which can ultimately lead to cracking, spalling, loss of integrity, and deterioration [52]. Sulfate attack susceptibility is typically measured by casting mortar bars that are stored in a sodium sulfate solution at room temperature and measured for up to 18 months. The standard used in the U.S. to test for sulfate attack susceptibility is ASTM C 1012: Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution [64].

Minimal sulfate attack research has been completed concerning concrete made with recycled concrete aggregates. Limbachiya et al. reported that expansions in mortar bars due to sulfate attack increased as the replacement ratio of RCA increased [50]. Dhir et al confirmed this with experiments that showed that expansions in mortar bars were similar to that of NAC up to a 30% coarse RCA replacement level. However, above a 30% replacement of RCA for NA expansions increased as RCA content increased, with a 52% increase in expansion over NAC at a 50% replacement level and a 68% increase in expansion over NAC at a 100% replacement level [21].

1.2.5   Alkali-Silica Reaction: Background, Testing Methods, and Occurrence and Mitigation in Concrete Made with Recycled Concrete Aggregates

Alkali-silica reaction (ASR) was first reported in the 1940s by Thomas E. Stanton. He observed that certain types of aggregates, when cast in concrete with cement of sufficient alkalinity and exposed to moisture, could result in expansion of that concrete that could eventually become deleterious to the concrete [65]. Since this discovery, ASR has become one of the leading causes of premature concrete deterioration in the world. It has been seen in almost every type of structure including buildings (with exterior exposure to moisture), dams, pavements, and bridges; and has been implicated in premature deterioration in almost every state in the United States [66].

ASR requires three conditions to occur:

1.   Available alkalis in the pore solution (mainly supplied by the cement);
2.   Reactive silica in the aggregates; and
3.   Sufficient moisture available.

If all three of these conditions are met, a highly alkaline and silica rich gel can form in and around the aggregates as well as in the pores of the concrete. The gel will absorb water from the surrounding pore solution and expand. This expansion causes a tensile force on the surrounding concrete matrix, and when this expansive pressure increases to be higher than the tensile capacity of the concrete, it can cause cracking. Cracks in concrete caused by alkali-silica reaction can allow the ingress of water into the system thus exposing the gel to more water and exacerbating the problem. Water ingress due to ASR cracking can also lead to deterioration from other durability mechanisms such as corrosion, freeze-thaw attack, and sulfate attack. If just one of the three conditions listed above is not met ASR will not occur. It is very difficult or even impossible to eliminate any of these conditions, however, and as a result there has been a significant amount of research performed since it was first discovered by Stanton to attempt to prevent or mitigate this reaction.

Although an extensive review of ASR mechanisms is not within the scope of this review, it is important to cover the basic mechanism by which it occurs. ASR is a chemical reaction that occurs between the reactive silica in the gel and the hydroxyl ions (OH) that are present in the pore solution. When amorphous or poorly-crystalline silica in an aggregate is exposed to

a high concentration of OH⁻, the hydroxyl ions can cause rupture of the bonds holding the silanol and siloxane groups within the structure of the aggregate. Equation 1-2 and Equation 1-3 illustrate the chemical reaction occurring.

$$\equiv Si - OH + OH^- \rightarrow \equiv Si - O^- + H_2O$$

Equation 1-2

$$\equiv Si - O - Si \equiv + OH^- \rightarrow 2 \equiv Si - O^- + H_2O$$
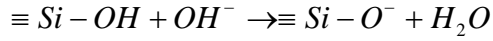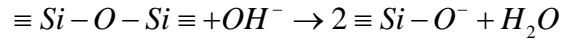
Equation 1-3

Subsequently, the negative charges on the oxygen atoms are balanced by the available alkalis (Na^+ and K^+) in the pore solution [67, 68]. An alkali-silica gel forms in and around the aggregates and within the pores of the concrete and is hygroscopic. As the gel absorbs water from the surrounding pore solution it expands, causing overall expansion of the concrete and can lead to cracking and deterioration of the concrete. The amount of expansion is controlled by the amount of available alkalis in the system, temperature, moisture content, and amount of restraining steel in the concrete [68].

The alkalis that are required for ASR can come from several different places, though portland cement contributes the majority of the alkalis in concrete. Other sources include:

- Supplementary cementing materials;
- Aggregates;
- Chemical admixtures; and
- Environment (e.g. seawater, deicing salts) [66].

The amount of alkalis in cement and SCMs is typically referred to by a sodium oxide equivalency, Na_2O_{eq}. The equation used to determine the sodium oxide equivalency can be seen in Equation 1-4 [66]:

$$Na_2O_{eq} = Na_2O + 0.658 K_2O$$

Equation 1-4

where:

Na_2O_{eq} = total sodium oxide equivalent, in percent by mass
Na_2O = sodium oxide content, in percent by mass
K_2O = potassium oxide content, in percent by mass

In Stanton's original work, he proposed that limiting the alkali content of the cement below 0.6% could prevent alkali-silica reaction from occurring [65]. This has even been incorporated as an optional composition maximum in ASTM C150: Standard Specification for Portland Cement [32, 69]. More recent work has shown that limiting the content of alkalis is not an effective enough measure on its own to prevent ASR [66]. This is due to the existence of pessimum effects. In some cases, an aggregate has shown to be reactive at low alkali levels, even though it tested as innocuous at higher alkali levels. This is known as a pessimum effect [70]. This is illustrated in Figure 1-4.
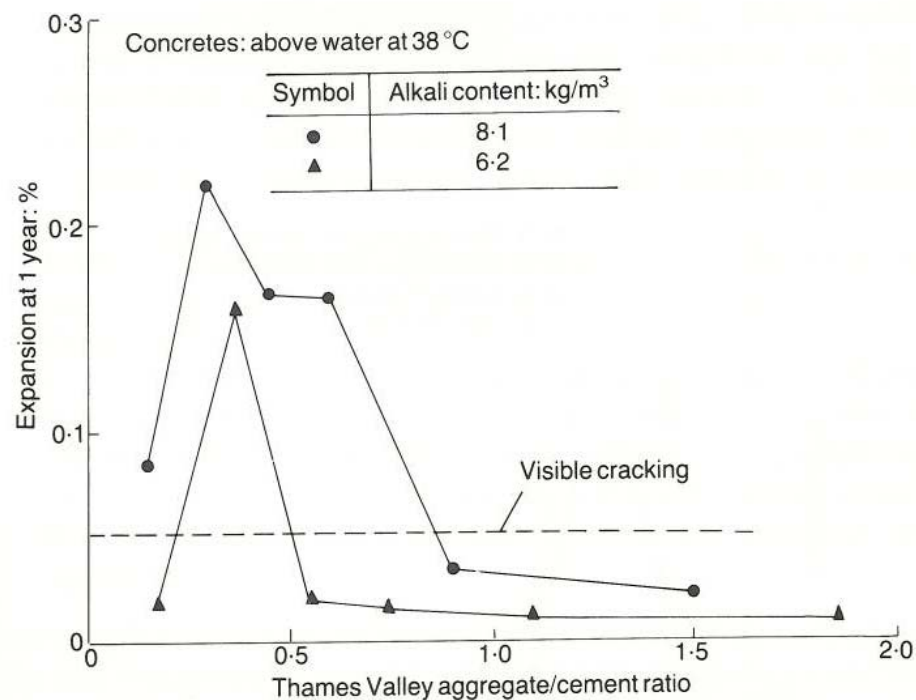
Figure 1-4: Pessimum effect in mortar bars made with Thames Valley aggregate [70]

This graph shows that, for this particular aggregate, the highest expansions are observed at lower overall contents of the reactive aggregate. This phenomenon is not completely understood but has been attributed to a change in the chemical reactions seen in ASR. At the peak expansion, the reactive silica content reduces either the alkali concentration or the hydroxyl ion concentration to a threshold level or it exhausts the available alkalis in the system [70]. It has been shown that the total alkali loading in the system may be of more importance [71]. For instance a concrete made with 650 lb/yd^3 of ASTM C 150 Type I cement having a 0.60 Na$_2$O$_{eq}$ cement has a total alkali loading of 3.9 lbs/yd^3 of equivalent

alkali. Whereas the same concrete using an ASTM C 150 Type I cement having a 0.80 Na_2O_{eq} would have a 5.2 lb/yd^3 equivalent alkali.

The reactive silica refers to poorly crystallized or amorphous silica contained within aggregates that is susceptible to breaking down under exposure to the highly alkaline environments seen in concrete [66]. Aggregates can also exhibit a pessimum effect where, for the same level of alkalis in a system, a smaller amount of aggregate (and therefore a smaller amount of reactive silica) will produce higher expansion levels in concrete. Rock types and reactive minerals that are commonly susceptible to ASR are [66]:

- Arenite
- Argillite
- Arkose
- Chert
- Flint
- Gneiss
- Granite
- Greywake
- Hornfels
- Quarz-arenite
- Quartzite
- Sandstone
- Shale
- Silicified carbonate
- Siltstone
- Cristobalite
- Microcrystalline quartz opal
- Strained quartz tridymite
- Volcanic glass

The available moisture required during alkali-silica reaction can come from a variety of places. There is water contained within the concrete in the pore solution present within the voids, and it is believed that a relative humidity as low as 80% is required to cause ASR expansion [66]. Other sources of moisture can come from the environment, particularly if there is cracking within the concrete matrix that allows the ingress of water into the system. Reducing the available moisture can limit the ASR-induced damage, though it is impossible to completely stop it in this method [66]. Aggregates can also exhibit a pessimum effect

where, for the same level of alkalis in a system, a smaller amount of aggregate (and therefore a smaller amount of reactive silica) will produce higher expansion levels in concrete.

Symptoms of ASR can be seen at both the micro- and macro-scales. Figure 1-5 shows a thin-cut section of concrete that has undergone ASR.
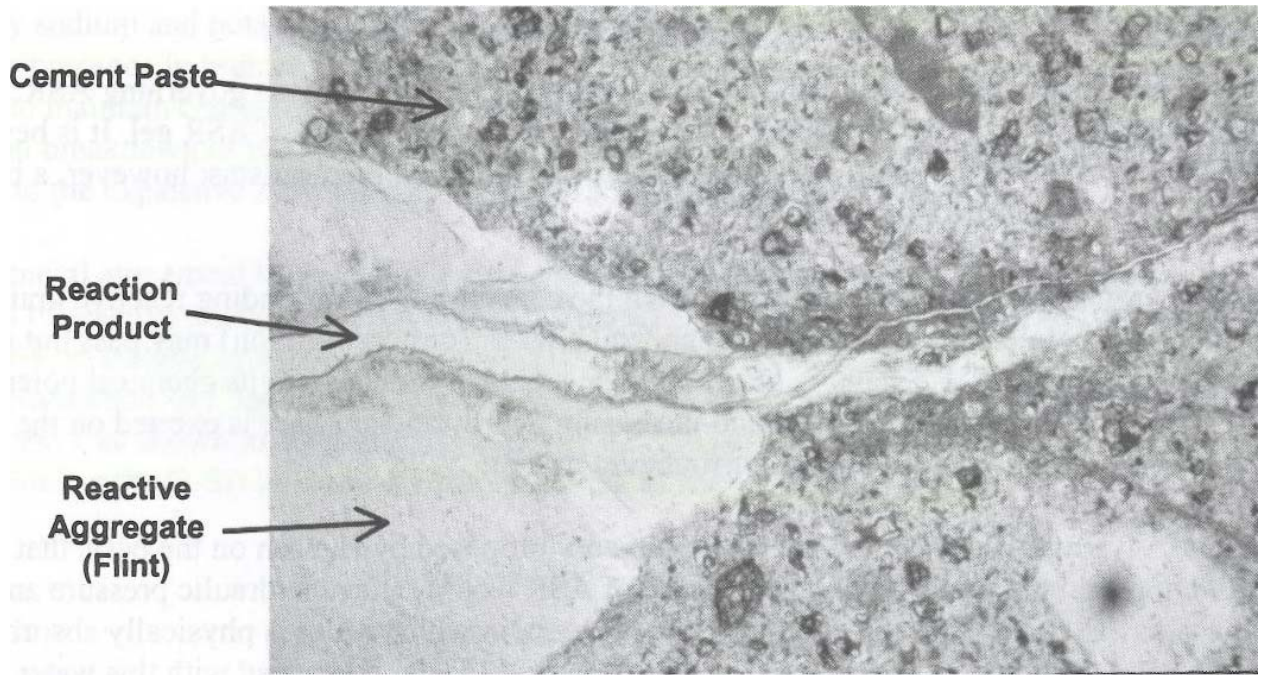
Figure 1-5: ASR damaged concrete, showing ASR gel and typical crack pattern [66]

The reaction product shown is the ASR gel that has formed in and around the aggregate, and cracked the aggregate and the surrounding concrete matrix [66]. Figure 1-6 shows map cracking on the face of a bridge parapet caused by ASR [72].

Figure 1-6: Bridge parapet showing ASR cracking [72]

Visible damage to structures due to ASR can vary depending on the severity of the attack, type of structure, restraint of structure, and exposure. The structural restraint has a particular influence on the manner in which cracks form. Unrestrained structures will typically form map cracking as seen in Figure 1-6, however cracking in restrained structures will often show close alignment with the direction of the main reinforcement [72].

Mitigating Alkali-Silica Reaction

Research into methods to mitigate or prevent ASR has been ongoing since its initial discovery by Stanton over 70 years ago. ASR can be eliminated completely by using non-reactive aggregates when making new concrete [32, 66]. This, however, is rarely feasible as non-reactive aggregates may not be locally available, or economically or environmentally viable to transport to the location. As discussed earlier limiting the alkali content of the concrete can also be effective in preventing ASR, however, this does not always work due to the existence of pessimum effects [66]. Preventing the ingress of water into the concrete matrix can also reduce expansions caused by ASR, however, this only slows down the reaction, and typically cannot prevent it from happening [66]. ASR can be arrested by reducing the relative humidity within the concrete to below 80% [73]. This can be very difficult or impossible to accomplish in field concrete, and as such is not an effective means for preventing ASR.

The most effective way currently known to mitigate ASR when using reactive aggregates is by using supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBFS), silica fume, metakaolin, and rice husk ash [32]. Lithium compounds have also been found to control ASR induced expansions in concrete [66]. Contained in this section is a review of materials used for mitigating ASR, specifically: fly ash, GGBFS, silica fume, and metakaolin.

Supplementary cementitious materials (SCMs) are materials that supplement concrete mixtures as an addition to or in place of portland cement. These materials are beneficial to the properties of the hardened concrete and can act either hydraulically or pozzolonically. They can be beneficial when added to concrete as they typically increase strength, increase workability (in the case of fly ash), mitigate ASR, modifying setting time, and decreasing permeability [74].

SCMs fall into two main categories: pozzolonic and hydraulic. Pozzolonic materials have high contents of amorphous silica that, when finely ground and added to concrete mixtures, react with calcium hydroxide (a product of cement hydration) and form cementitious compounds, primarily C-S-H, calcium-silicate-hydrate (another main hydration product in cement hydration). Examples of pozzolonically acting SCMS are Class F fly ash, metakaolin, clay, shale, rice husk ash, and silica fume [32]. Hydraulic SCMs are materials that react with water to form hydration products with cementing properties. Examples of hydraulic SCMs are GGBFS, Class C fly ash, and hydraulic hydrated lime [52]. Table 1-3 shows the physical properties of individual common SCMs.

Table 1-3: Physical properties of portland cement and common SCMs [75]

Material	Specific gravity	Surface area ft^2/lb (m^2/kg)	Bulk density lb/ft^3 (kg/m^3)	Particle diameter in (μm)	% replacement (By mass)	Color	Reaction Type
Portland Cement	3.15	1700 (350)	50-100 (830-1650)	3.9E-4 - 5.9E-4 (10.0-15.0)	/	Tan	Hydraulic
Fly Ash - Class C	1.9-2.8	1450-2450 (300-500)	34-54 (540-860)	avg: <7.9E-4 (avg: <20)	15-40	Tan	Hydraulic
Fly Ash - Class F	1.9-2.8	1450-2450 (300-500)	34-54 (540-860)	avg: <7.9E-4 (avg: <20)	15-40	Brown	Pozzolanic
Silica Fume	2.20-2.5	100000 (20000)	8-27 (130-430)	avg: <3.9E-6 (avg: <0.1)	5.0-10	Black	Pozzolanic
Slag	2.85-2.95	1950-2930 (400-600)	66-86 (1050-1375)	<0.0018 (<45)	30-50	White	Hydraulic
Metakaolin	2.40-2.61	3200-6600 (650-1350)	19-25 (300-400)	3.9E-5 - 7.9E-5 (1.0-2.0)	7-35	White	Pozzolanic

The highly spherical nature of particles such as fly ash and GGBFS, or slag, promote workability, whereas the extremely fine particles such as silica fume react extremely fast during hydration due to its high surface area and lead to mixtures that are more difficult to work with. However, the extremely fine nature of silica fume allows for particle packing in the concrete matrix, and thus provides a more dense hardened concrete [32].

Table 1-4 shows the effect on concrete properties of specific SCMs. A "-" indicates a negative effect and a "+" sign indicates a positive effect.

Table 1-4: Effects of SCMs on concrete properties [75]

Material	Workability	Early-Age Strength	Long-term Strength	ASR Mitigation
Silica fume	--	++	+++	+
Class C Fly ash	++	+++	++	+
Class F Fly ash	++	-	++	+++
Metakaolin	-	+	++	+++
GGBFS	negl	-	++	++

SCMs are typically by-product materials of manufacturing processes or are natural materials. In addition to their beneficial properties when used in concrete, the use particularly of the

by-product materials is desirable from a sustainability view point as it prevents these materials from being land-filled and using them as a replacement for portland cement can lower the overall carbon footprint of the concrete [32, 52]. Natural SCMs are SCMs that are produced specifically for use in concrete and typically come from volcanic rocks and minerals. These materials need to go through certain levels of processing to be used in concrete, these includes grinding or heat treatments [52].

<u>Fly Ash</u>

Fly ash is the most commonly used SCM for mitigating ASR in concrete. Fly ashes are separated into two different categories: class C fly ash and class F fly ash. Both are a by-product of the coal burning industry with class F coming from the burning of bituminous coals and class C from the burning of lignitic coals [32]. Class C fly ash contains high amounts of calcium oxide (greater than 10% by mass), and a minimum silicon dioxide plus aluminum oxide plus iron oxide content of 50% by mass. Class C fly ashes react in a hydraulic fashion when mixed with water, though the material will exhibit some pozzolonic reactions as well. Class F fly ashes contain a minimum silicon dioxide plus aluminum oxide plus iron oxide content of 70% by mass. Class F fly ash typically reacts in only a pozzolonic manner [74].

Fly ash has been shown to effectively mitigate the expansions due to ASR in concrete when used as a replacement for portland cement [68, 71, 76, 77]. The replacement level required varies depending on the chemical composition of the portland cement, reactivity of the aggregate, and the chemical composition of the fly ash used. Shehata and Thomas reported that with a particular fly ash, a replacement rate of 60 percent was required to mitigate the expansion due to ASR in their test specimens [76]. It is important to note that the American Concrete Institute limits the amount of fly ash replacement levels to 25% in structural concrete [78]. While the mechanism behind fly ash's ability to mitigate ASR is not completely understood, it is well known that the class F fly ashes (lower calcium oxide contents) typically mitigate ASR better than than class C fly ashes [76]. It has been postulated that ASR gels with high amounts of calcium are less viscous than their counter parts with low calcium contents, thus as they swell they are not as easily dissipated and cause more cracking. However, the use of more pozzolonic fly ashes (class F) consumes more calcium hydroxide

in the concrete, thus lowering the availability of calcium for the ASR gel, and reducing expansions [79].

A study was performed by Malvar and Lenke to determine the efficiency of a fly ash, and thus the replacement needed to mitigate ASR expansions. This involved analyzing the input of various chemical constituents of both fly ash and cement. From this, they were able to develop an equation that allows the user to input the chemical constituents and receive a result of the mass percent of fly ash needed to replace cement to control the reaction [77]. They divided the chemical constituents of cement and fly ash into two groups: (1) constituents that promoted ASR and (2) constituents that prevent ASR. The constituents that were classified as promoting ASR were calcium oxide (CaO), alkalis (Na_2O and K_2O, expressed as Na_2O_{eq}), magnesium oxide (MgO) and sulfur trioxide (SO_3). The constituents that worked to prevent ASR were identified as silicon dioxide (SiO_2), aluminum trioxide (Al_2O_3), and iron oxide (Fe_2O_3). These were then expressed as calcium oxide equivalents (CaO_{eq}) and silicon dioxide equivalents (SiO_{2eq}), seen in Equation 1-5 and Equation 1-6, respectively. Oxide contents were entered as percent mass of total fly ash or portland cement [77].

$$CaO_{eq} = CaO + 0.905Na_2O_{eq} + 0.595K_2O + 1.391MgO + 0.700SO_3$$

Equation 1-5

$$SiO_{2eq} = SiO_2 + 0.589Al_2O_3 + 0.376Fe_2O_3$$

Equation 1-6

Weighting factors were also developed to account for the difference in reactivity between the various chemical constituents and were then applied to the calcium oxide and silicon dioxide equivalents. These were determined to be $\alpha=5.64$ and $\beta=1.14$, respectively. They were applied as seen in Equation 1-7 and Equation 1-8 [77].

$$CaO_{eq\alpha} = CaO + \alpha(0.905Na_2O_{eq} + 0.595K_2O + 1.391MgO + 0.700SO_3)$$

Equation 1-7

$$SiO_{2eq\beta} = SiO_2 + \beta(0.589Al_2O_3 + 0.376Fe_2O_3)$$

Equation 1-8

A set of constants were also developed that changed depending on the level of reliability required by the user to determine how much fly ash would be needed to reduce ASR expansions. For a 90% reliability level that ASR would be mitigated values used by Malvar

and Lenke were: $a_1=0$, $a_2=1.0244$, $a_3=0.6696$, and $a_4=0.1778$. Finally, the percent mass replacement of fly ash required to mitigate ASR using a specific combination of aggregate, cement, and fly ash was determined to be [77]:

$$W = \frac{1 - g(\frac{0.08}{E_{14c}})}{(1 - \frac{CaO_{eq\alpha fa}}{CaO_{eq\alpha c}}) - (1 - \frac{SiO_{2eq\beta fa}}{SiO_{2eq\beta c}}) g(\frac{0.08}{E_{14c}})}$$

Equation 1-9

Where:

W = mass percent replacement of fly ash required to mitigate ASR
E_{14c} = Percent expansion of mortar bars in the accelerated mortar bar test at 14 days

$$g = \frac{a_4(\tanh^{-1}(\frac{2(\frac{0.08}{E_{14c}}) - (a_1 + a_2)}{a_2 - a_1}) + a_3}{\frac{0.08}{E_{14c}}}$$

$CaO_{eq\alpha fa}$ = Calcium oxide equivalent, with the alpha factor applied, for the fly ash
$CaO_{eq\alpha c}$ = Calcium oxide equivalent, with the alpha factor applied, for the portland cement
$SiO_{2eq\beta fa}$ = Silicon dioxide equivalent, with the beta factor applied, for the fly ash
$SiO_{2eq\beta c}$ = Silicon dioxide equivalent, with the beta factor applied, for the portland cement

It is important to note that this equation was developed empirically based on the evaluation of five studies using twenty-nine fly ashes and five aggregates. The chemical index equations may not be accurate for all combinations of materials and testing should always be performed prior to using the fly ash replacement level stipulated by this formula in field concrete. The equation does, however, provide a starting point for engineers to use to develop the appropriate fly ash replacement dosage to mitigate ASR. This can then be evaluated through laboratory testing (e.g. ASTM C 1567 or ASTM C 1293) to determine the exact amount of fly ash needed to control the alkali-silica reactivity of a particular aggregate.

Ground Granulated Blast Furnace Slag

GGBFS is a by-product of the steel-making industry. It is made from iron blast-furnace slag, and is a nonmetallic hydraulic cementitious material that contains mostly silicates and

aluminosilicates. The molten slag is rapidly quenched in water, and then ground down to a fine powder [74]. GGBFS has been shown to reduce the expansions in concrete due to ASR, however, not as effectively as fly ash or other mitigation options [80] at similar replacement levels. GGBFS works to mitigate ASR by producing C-S-H with a high silica to calcium ratio, which binds significant amounts of alkalies preventing ASR [66]. A study by Thomas showed that up to 20% more slag was required than class C fly ash to reduce ASR induced expansions in test specimens to within acceptable limits [68].GGBFS is typically used at dosage rates of 35 – 50% by mass of cement to prevent ASR, though higher replacement levels may be necessary [66]. The American Concrete Institute limits the inclusion of GGBFS to 50% of the cementitious materials in structural concrete [78].

Silica Fume

Silica fume is a by-product of the silicon metal and ferrosilicon alloy industries. It is produced when silicon oxide vapors (from the reduction of quartz to silicon at high temperatures) condense to very small spherical particles. It is typically finer by about two orders of magnitude than typical portland cements [52]. Silica fume also prevents ASR by binding alkalis within the C-S-H structure [68]. Boddy et al. observed that silica fumes with higher silicon dioxide contents are more effective at binding alkalis [81]. Silica fume has been shown to be able to mitigate ASR at relatively low replacement levels (5-10%) [68, 82, 83]. Higher replacement levels may be necessary for concretes with high alkali contents [68]. However, additions above 10% are prohibited by the American Concrete Institute for concrete exposed to deicing chemicals [78]; higher replacement levels will also have an adverse effect on workability, and should be avoided [52].

Metakaolin

Metakaolin has also been shown to be an SCM that is effective in reducing ASR induced expansions. Metakaolin is a natural pozzolan that is produced through low-temperature calcinations of high purity kaolin clays [74]. Metakaolin has a high aluminum oxide content (typically around 45%) [74]. It is believed that the introduction of alumina causes the C-S-H structure to form C-A-S-H (calcium alumino silicate hydrate) which has an even greater capacity to bind alkalis than C-S-H [68, 84]. Replacement rates between 5-20% have been

able to reduce ASR induced expansion to within acceptable limits [68, 80, 84]. Higher replacement levels should be avoided, however, due to workability loss from using the metakaolin [52].

<u>Ternary Blends</u>

As discussed individually above, it is not always possible to create binary blends of portland cement and SCMs due to code restrictions or adverse affects of the SCM at higher replacement levels [52, 78]. However, ternary and quartenary blends involving portland cement and two or three SCMs have proven to be useful providing the necessary level of mitigation without exceeding the code restrictions. The American Concrete Institute allows for blends up to total replacement levels of 50% [78]. The effect of ternary blends is illustrated in Figure 1-7.
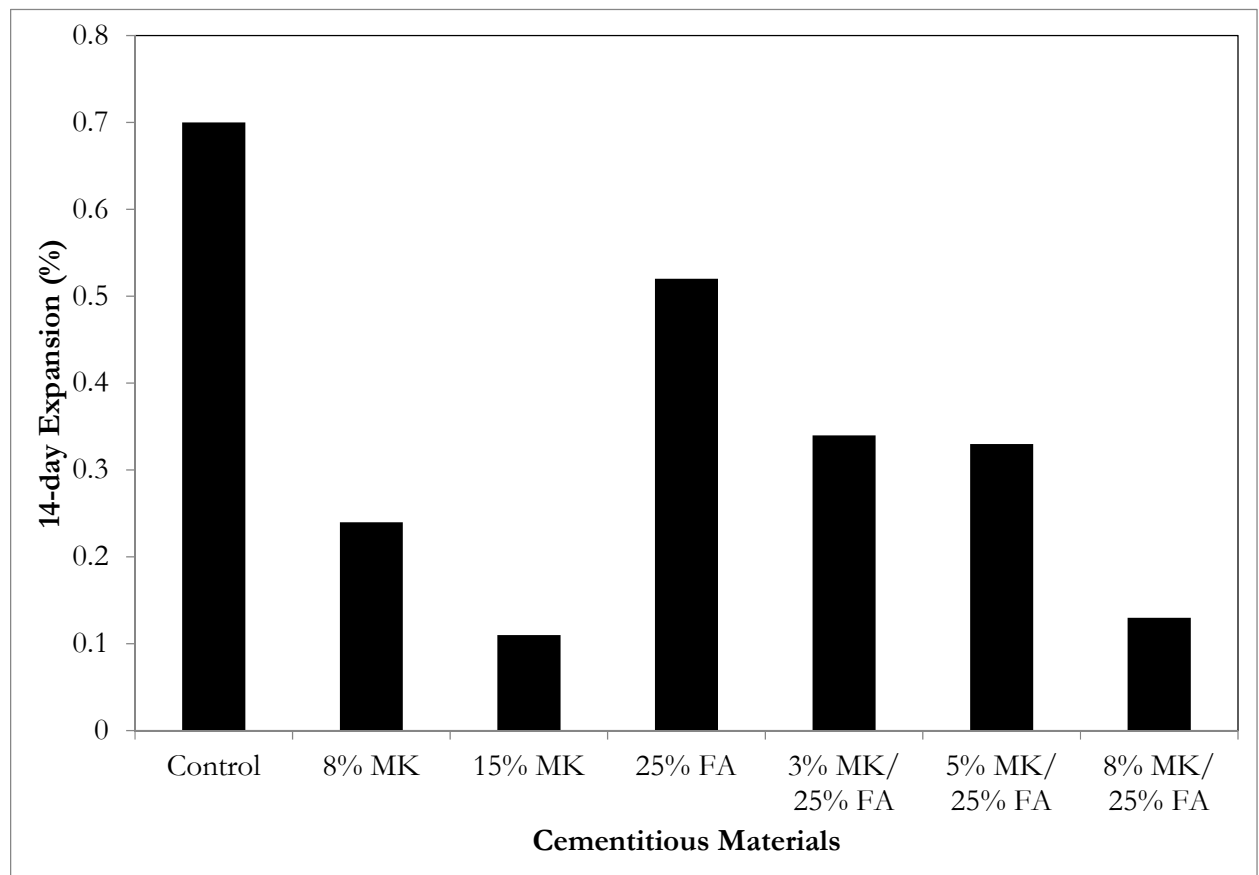
Figure 1-7: Efficacy of ternary blends to reduce expansions caused by ASR [85]

This figure shows data from the work presented by Moser et al., which shows that the ternary blend of the 8% metakaolin (MK) and 25% fly ash (FA) replacement levels were able to reduce ASR induced expansions better than either SCM was able to individually [85]. When using ternary and quartenary blends it is actually possible to reduce expansions greater than the sum of the individual SCM's reduction, e.g. the effects are synergistic not merely cummulative [86]. Therefore, alternatives to simple binary blends of portland cement and SCMs should be explored when working with a highly reactive aggregate.

Alkali-Silica Reaction Test Methods

There are several test methods that have been developed to detect the alkali-silica reactivity of aggregates. These test methods range from tests on aggregates, mortar, and concrete, to petrographic examination of aggregates and concrete. There have also been modifications to these tests which allow for the use of SCMs in the mixture to test their efficacy on mitigating the reactivity of the aggregates. Although an exhaustive review of all ASR test methods is not part of the scope of this review, a few important test methods are described in detail in the following section. This list includes the ASR test methods used in the current research. Table 1-5 provides a brief overview of the test methods described in detail. The overview includes the test number and name, specimen size, aggregate gradations, a short description of the test, and expansion criteria, further information follows.

Table 1-5: Recommended tests for detecting alkali-silica reactivity

ASTM Test Method	Specimen Size	Aggregate Type	Description	Expansion Limits
Mortar				
ASTM C1260: Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)	1 x 1 x 11.25 in. (25 x 25 x 285 mm) prism with 10 in (250 mm) effective guage length	Fine Aggregate: Gradation: 0.0059 - 0.157 in. (150 µm - 4mm) diameter	Often referred to as the accelerated mortar bar test (AMBT). Detects potentially deleterious reactivity of aggregate within 16 days of casting. Bars are stored for 14 days in 1 N NaOH at 176 °F (80 °C) during duration of test.	When measured at 16 days after casting: Exp < 0.10% indicates innocuous behavior. Exp > 0.20 % indicates potentially deleterious expansion. Exp. Between 0.10% and 0.20% may indicate deleterious or innocuous behavior, supplementary tests required.
ASTM C1567: Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method)	1 x 1 x 11.25 in. (25 x 25 x 285 mm) prism with 10 in (250 mm) effective guage length	Fine Aggregate: Gradation: 0.0059 - 0.157 in. (150 µm - 4mm) diameter	Also referred to as the AMBT. Prisms cast and stored according to standard AMBT test (ASTM C 1260). Tests the effectiveness of SCMs within 16 days of casting.	When measured at 16 days after casting: Exp. < 0.1% indicate combinations of SCMs that will mitigate ASR effectively. Exp. > 0.10% indicate combinations of SCMs and aggregates that may produce potentially deleterious expansions, supplementary testing in ASTM C1293 should be performed.
Concrete				
ASTM C1293: Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction	3 x 3 x 11.25 in (75 x 75 x 285 mm) prism with 10 in (250 mm) effective guage length	Fine and Coarse Aggregate. Fine aggregate: Use as graded from quarry. Coarse aggregate: Gradataion: 0.187 - 0.750 in (4.75 - 19 mm) diameter	Often referred to as the concrete prism test (CPT). Test specimens are cast with boosted alkali contents (1.25% Na_2O_{eq}) and stored at 100 °F (38 °C). Test is run for 1 year, though is extended to 2 years if testing with combinations of SCMs. The CPT is considered to be the best indicator of aggregate reactivity.	When measured at 1 year (or 2 for combinations of SCMs) after casting: Exp > 0.04% indicate a potentially deleterious expansion.

<u>ASTM C1260: Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)</u>

The ASTM C1260 test is one of the most common tests used to determine reactivity because it can be completed rapidly, in just 16 days. In this test, mortar prisms that measure 1 x 1 x 11.25 in. (25 x 25 x 285 mm) are cast at a fine aggregate to cement ratio of 2.75:1 and a w/cm of 0.47. A stainless steel gage stud is cast into both ends of each bar to provide an effective 10.00 ± 0.10 in. (254 ± 2.54 mm) gage length. After curing for 24 ± 2h in 95% or higher relative humidity and 73 ± 3°F (23 ± 2°C), the mortar bars are submerged in tap water and placed in a 176 ± 3.6°F (80 ± 3.6°C) oven where they equilibrated before the next reading. The initial, or zero, reading of the bars is taken 24 ± 2h later and the bars are quickly

transferred to a solution of 1 N NaOH which is already at 176 ± 3.6°F (80 ± 3.6°C). The bars then remain in 1 N NaOH at 176 ± 3.6°F (80 ± 3.6°C) for a period of 14 days [87]. Several measurements are taken throughout this time period at approximately the same time each day. Length change is recorded to the nearest 0.0001 in. (0.0025 mm) and results are presented for the average of three prisms to the nearest 0.01%.

An AMBT mortar bar can be seen in a comparator, which is used to measure the expansion in Figure 1-8a; a typical storage container for these bars can be seen in Figure 1-8b; an oven used to store the bars submerged in 1 N NaOH can be seen in Figure 1-8c; and a typical mixer used for making the mortar bars can be seen in Figure 1-8d.

a   b

c   d

Figure 1-8: AMBT test equipment

Expansion criteria for this test fall into three categories as specified by ASTM C 1260 based on expansion measured 16 days after casting (14 days after immersion in 1 N NaOH). Average expansion of less than 0.10% is generally considered to be indicative of innocuous behavior. Expansions of more than 0.20% indicate that the aggregates are potentially deleterious. Expansions that fall between 0.10 and 0.20% indicate that the aggregate may exhibit either innocuous or deleterious performance in the field [87]. The above expansion criteria, as described in ASTM C 1260, are not actually used by many researchers or agencies, but rather, the consensus among certain ASR researchers and engineers is to use an expansion limit of 0.10% after 14 days of immersion in the soak solution to indicate aggregate reactivity [88]. Other testing agencies and researchers monitor the specimens longer, typically to 28 days after initial submersion in the 1 N NaOH solution, with continued periodic measurements. Also, different expansion limits may be applied. However, research has shown that using the 0.10% expansions limit at a 28-day expansion does not correlate as well with field performance as a 0.10% expansion limit at 14 days; some aggregates will register as "potentially deleterious" when they actually perform satisfactorily in the field [88].

The within laboratory precision for this test states that, for expansions greater than 0.1%, the average coefficient of variation is 2.94% at 14 days, and the difference between three different prisms should not exceed 8.3% from the mean expansion. The multi laboratory precision for this test states that, for expansions greater than 0.1%, the average coefficient of variation is 15.2% at 14 days, and the difference between three different prisms should not exceed 43% from the mean expansion [87].

It is important to note that this test is only applicable to mortar. If a coarse aggregate's reactivity is to be assessed using the ASTM C1260 method, it must be crushed to meet the gradation requirements of the test. The gradation requirements can be seen in Table 1-6.

Table 1-6: ASTM C1260 test aggregate gradation

	Mass %	10	25	25	25	15
Sieve Size in (mm)	Retained On	0.0937 (2.36)	0.0469 (1.18)	0.0234 (0.6)	0.0117 (0.3)	0.0059 (0.15)
	Passing	0.157 (4)	0.0937 (2.36)	0.0469 (1.18)	0.0234 (0.6)	0.0117 (0.3)

As a result of the aggregate processing, it is possible to expose or remove reactive phases in the aggregate [87]. Research has shown that the microstructural characteristics of an aggregates can significantly affect its alkali-silica reactivity [89]. The crushing and washing process to obtain an aggregate gradation of the appropriate size can alter the textural characteristics of the aggregate, and thus cause the aggregate to exhibit higher or lower levels of reactivity than its coarser fractions. Du-you et al. described that for an aggregate where the reactive siliceous material acted as a cementing material between quartz grains; the reactivity in the AMBT test was low compared to its actual reactivity because the crushing procedure removed a large amount of the reactive siliceous material [90]. The ASTM C1260 standard does note that this effect may occur specifically with some granitic gniesses or metabasalts [87]. However, for a different aggregate that has shown relatively little reactivity in field performance, when crushed and used in the AMBT test it showed to be extremely reactive [90].

ASTM C1567: Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate

A test to use the AMBT method to determine the efficacy of using SCMs to mitigate the alkali-silica reactivity of aggregates was not developed until 2004 [88] even though research had shown that it was able to assess the reactivity of combinations of cementitious materials and aggregates [91]. ASTM C1567 was developed out of modifications to the ASTM C1260 test [88], and subsequently uses the same testing procedure but uses combinations of cement, SCMs and reactive aggregate, instead. The cementitious materials, therefore, are various combinations of portland cement, and SCMs such as fly ash, ground granulated blast furnace slag, metakaolin, silica fume or other SCMs. However, the overall amount of cementitious materials is the same. Tests can be run to assess the ability of a single SCM in

combination with portland cement, or of blends of multiple SCMs with portland cement [92]. Aggregates evalauted in the ASTM C1567 test should be tested according to the ASTM C1260 procedures as well (with just the portland cement, no SCMS), so the results of the ASTM C1260 test and the ASTM C1567 test can be compared to determine the mitigating efficacy of the SCMs used [92].

It is recommended that when using pozzolans with an alkali content greater than 4.0% as SCMs, that the ASTM C1293 test be run, because the test (ASTM C 1567) may underestimate the expansion of systems containing SCMs with higher alkali contents [76, 92]. The standard also allows for the use of a high range water reducer (HRWR) if necessary when using metakaolin or silica fume. However, the w/cm ratio must remain at a 0.47 (thus, if using a liquid HRWR, the water content must be adjusted to include the water contributed from the HRWR) [92]. The alkali content of the HRWR should also be monitored as it may have an effect on the expansion of the mortar bar during the test [93].

The expansion criteria for this test states that combinations of cement, SCMs, and aggregates that expand more than 0.10% at 16 days after casting (14 days after submersion in 1 N NaOH solution) indicate potentially deleterious expansions [92].

The within laboratory precision for this test states that, for expansions greater than 0.1%, the average coefficient of variation is 2.94% at 14 days, and the difference between three different prisms should not exceed 8.3% from the mean expansion. The multi laboratory precision for this test states that, for expansions greater than 0.1%, the average coefficient of variation is 15.2% at 14 days, and the difference between three different prisms should not exceed 43% from the mean expansion [92].

ASTM C1293: Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

Commonly referred to as the concrete prism test (CPT), ASTM C1293 is generally considered the most accurate test method for determining the alkali-silica reactivity of an aggregate. This is because it uses a larger specimen, a full scale concrete mixture, and a testing environment that is less harsh than that of the ASTM C1260 or ASTM C1567 tests

[66]. In this test, concrete prisms that measure 3 x 3 x 11.25 in. (75 x 75 x 285 mm) are cast with a stainless steel gage stud cast into both ends of each bar to provide an effective 10.00 ± 0.10 in. (254 ± 2.54 mm) gage length. The prisms are cast using an ASTM C150 Type I portland cement with a total alkali content of $0.9 \pm 0.1\%$ Na_2O_{eq}. Sodium hydroxide solution is added to the concrete mixing water to increase the total alkali content of the mixture to a 1.25% Na_2O_{eq} [94].

If a fine aggregate's reactivity is to be evaluated it should be cast with a non-reactive coarse aggregate; and subsequently, if a coarse aggregate's reactivity is to be evaluated, it should be cast with a non-reactive fine aggregate. A non-reactive aggregate (either fine or crushed coarse) is defined to be an aggregate that has an expansion of less than 0.10% at 14 days after submersion in a 1 N NaOH solution in the accelerated mortar bar (ASTM C1260) [94].

The concrete prisms are removed from their molds after curing for 23.5 ± 0.5h in a moist environment. The mortar bars are then kept in their storage containers at a temperature of $100 \pm 3.6°F$ ($38 \pm 2°C$). The prisms are kept in 5-gallon (18.9 liter) buckets that are fitted with racks to elevate the prisms about 1.5 in (38 mm) above the bottom of the bucket. The bucket is then filled with 0.8 ± 0.02 inches (20.3 ± 0.5 mm) of tap water. An absorbent wicking material is placed around the inside of the bucket that extends the full height of the bucket. The prisms are measured when they are demolded for an initial reading, and then measured subsequently at 7, 28, and 56 days, as well as 3, 6, 9, and 12 months. Length change is recorded to the nearest 0.0001 in. (0.0025 mm) and results are presented for the average three prisms to the nearest 0.01% [94]. The current ASTM standards allows for the use of the ASTM C1293 test to determine the efficacy of SCMs to mitigate the alkali-silica reactivity of aggregates. The standard suggests in the nonmandatory requirements that the test be expanded to two years when testing SCM efficacy [94].

A CPT prism can be seen in a comparator, which is used to measure the expansion in Figure 1-9a; and a typical storage container for these prisms can be seen in Figure 1-9b.
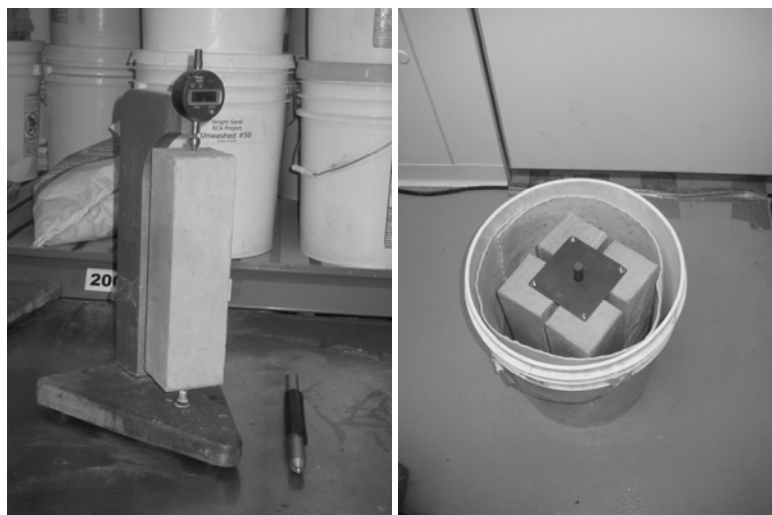
a   b

Figure 1-9: CPT test equipment

The expansion criteria for this test fall into two categories. Expansions of concrete specimens less than 0.04% at 1 year (2 years when using SCMs) are considered to be innocuous; expansions greater than 0.04% at 1 year (2 years when using SCMs) are considered to be potentially deleterious levels of expansion [94, 95]. No information is given stating whether expansions of exactly 0.04% indicate deleterious levels of expansion.

The multi-laboratory precision for this test falls into two categories. For average expansions less than 0.014%: the standard deviation of a single test results is 0.0032% and the results of a test in performed in two different laboratories on the same aggregate shall not differ by more than 0.009%, nineteen times out of twenty. For average expansions greater than 0.014%; the multi-laboratory coefficient of variation is 23%, and the results of a test in performed in two different laboratories on the same aggregate shall not differ by more than 65% of their average, nineteen times out of twenty [94].

The within laboratory precision for this test also falls into two categories. For average expansions less than 0.02%: the multi-specimen standard deviation is 0.00255 and the difference between three individual prism measurements shall not exceed 0.008%, nineteen times out of twenty. For average expansions greater than 0.02%; the multi-specimen

coefficient of variation is 12%, and the difference between three different prisms should not exceed 40% nineteen times out of twenty [94].

<u>Discussion on Reliability of Test Methods</u>

Research presented by Thomas et al. showed that in a comparison of results between the AMBT and the CPT the results from the two correlated 77% of the time. Of particular concern was the 7% of the time that the AMBT predicted innocuous behavior but the CPT showed the aggregate to cause potentially deleterious expansions [88]. Because of this potential outcome, it is recommended in the ASTM C1293 standard that the ASTM C1260 and ASTM C1567 tests always be run concurrently with ASTM C1293 testing [94]. The results of the ASTM C1260 test can be used while waiting for data from the longer ASTM C1293 test [88].

Alkali-Silica Reaction in Concrete Made with Recycled Concrete Aggregates

A 2003 study by the Federal Highway Administration performed an in-depth examination of the use of RCA in the United States. As a part of this they interviewed five states which have well developed RCA use programs. Two of these five states, Minnesota and California, noted specifically that the potential for ASR reactivity of RCA when used in new concrete was a concern when considering the use of RCA in pavements, structures, and non-structural concrete [7]. This concern was echoed in a study by Melton who stated that one of the biggest concerns in using RCA was the potential for ASR deterioration affecting the long-term performance of the concrete [8]. Beyond just the concern of RCA coming from concrete that was noted to have ASR deterioration is the concern that potentially reactive RCA could be produced from concrete that exhibited no signs of distress; such as an interior floor slab that was built using reactive aggregates but was not provided with enough moisture to cause deleterious expansions in its lifetime [55]. A study by Gress et al. showed that ten of sixteen pavements made with RCA in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming (with the new pavements ranging between 21 and 26 years old) showed evidence of ASR; though at the time of the study (2003) they were still performing satisfactorily. Only one of these pavements, however, was noted to have been made with RCA that came from pavement that had previously deteriorated due to ASR [96]. These

concerns show the need to develop research and data that support test methods to predict the reactivity of RCA when used in new concrete.

Several studies have been performed to understand the reactivity of RCA, particularly from sources of concrete that have experienced ASR deterioration. A study by Desmyter and Blockmans performed a study on the alkali-silica reactivity of RCA that was produced from a bridge that was demolished due to ASR deterioration [4]. The original natural coarse aggregate in the RCA was a river gravel which contained reactive chert components. RCA was used at a 100% coarse aggregate replacement level, and a non-reactive sand was used for the fine aggregate. A version of the concrete prism test was performed according to the French standard NF P-18-587:1990. The CPT has several different versions depending on the country and testing standard that is used. The French standard used hererequires that the test run for eight months, as opposed to the 12 months required by ASTM C1293; however the expansion limit is the same as in the ASTM C1293. The study performed two replicate CPTs using the same mixture design and testing method. The results indicated that their prisms did not expand above the 0.04% expansion limit for the CPT at eight months, and the trend actually showed shrinkage of the prisms after four months. The authors attributed this to the depletion of reactive components in the aggregates, considering they had been reacting in the field for a significant period of time before being recycled and reused in new concrete [4]. No further evidence was given to support this theory. If this were the case, the expansion would have stopped increasing; however, shrinkage would not have occurred. The evidence of shrinkage after the four month mark indicates that there may have been moisture loss in the containers, which can cause shrinkage.

Gress and Kozikowski also used the CPT as well as a modified AMBT which incorprated RCA produced from an interstate in Wyoming that had exhibited ASR damage [97]. The original natural aggregate in the RCA was comprised of a variety of rocks including: granite, basalt, diorite, rhyolide, and andesite. The authors' modified AMBT consisted of using the standard concrete prism size used in the ASTM C1293 test (3 x 3 x 11.25 in. (75 x 75 x 285 mm)), however it was placed in the ASTM C1260 storage environment (submerged in 1 N NaOH solution, and stored at 176°F (80°C)). The authors modified the test because there was concern that crushing the RCA to the gradation required by the ASTM C1260 test

would destroy the integrity of the RCA aggregate, and thus alter expansion results. No expansion limits were proposed for this modified test version. The test was able to show that the RCA was reactive and could potentially cause ASR. However, the use of the modified test procedure prevents correlation with other results on testing with RCA. The authors were able to show that alkali contents of the cement affected reactivity, with higher alkali cements resulting in higher expansions compared to prisms made with lower alkali cements. The results for the CPT test were only given through 28 weeks (standard length is one year). These results showed that the CPT was able to detect reactivity, however as of 28 weeks the expansion had not exceeded the CPT expansion limit of 0.04% (0.03% at 28 weeks)[97]. Similar to the study performed by Desmyter and Blockmans, it is difficult to make broad conclusions based off of tests completed on a single aggregate. Also, because both Gress and Kozikowski, and Desmyter and Blockmans did not use the same version of the CPT, it is difficult to compare their results.

Work by Shayan and Xu was the first to compare the performance of an RCA in both the standard accelerated mortar bar and concrete prism tests. Their results showed an RCA that presented as causing potentially deleterious expansions according to the AMBT, with an expansion of 0.28% and 0.39% at 14 and 21 days, respectively, after submersion in 1 N NaOH solution (the authors used an expansion limit of 0.10% at 21 days). The same aggregate was then run in the CPT and resulted in innocuous behavior with expansions of 0.01% at one year [31]. The authors attributed this to the ONA used in the RCA, a basalt/dolerite, that has been shown to fail the AMBT, but does not cause deleterious expansions in concrete. These contradictory results confirmed that further research is required into understanding the applicability of these test methods when using RCA.

A study was performed by Scott and Gress that also compared the results of both a modified and an unmodified ASTM C1260 results with ASTM C1293 results, and examined mitigation options using a class F fly ash and GGBFS, as well as lithium nitrate [98]. The aggregate was produced from a section of interstate in Maine that had exhibited ASR deterioration. The ONA was a fine grained quartzite commonly known as bluerock. The unmodified ASTM C1260 mortar bars that were cast, however, were done so using RCA that had had all the

mortar removed. Therefore, these results are not really applicable to studies using RCA, as this would be a reclaimed aggregate, and not a recycled concrete aggregate.

Scott and Gress's modified ASTM C1260 test uses the same prism as in the ASTM C1293, cast with coarse and fine aggregate, but it is then submerged in 1 N NaOH and measurements are taken to 28 days (56 days when testing combinations of aggregates and SCMs). Scott and Gress listed the failure criteria for this test as expansions that exceed 0.04% within 28 days (56 days when testing combinations of aggregates and SCMs) may indiciative of potentially deleterious behavior [98]. This modified version of the test was performed because it did not require crushing of the material, which may have altered the characteristics of the RCA. The RCA used in this modified ASTM C1260 test did not have its mortar removed. The RCA incorporated in the ASTM C1293 tests performed by Scott and Gress also did not have its adhered mortar removed. RCA was used at a 100% replacement level for the coarse aggregate in both the modified ASTM C1260 and the ASTM C1293 tests.

The authors observed that the results of the unmodified ASTM C1260 test using reclaimed aggregate and the ASTM C1293 results correlated. Both tests indicated that the aggregate would cause deleterious expansions in the field [98]. However, since the RCA used in the unmodified ASTM C1260 test for this study did not contain the adhered mortar, the results from the two tests should not be correlated because they are essentially comparing two different aggregates.

A study of mitigation methods showed that using a 25% fly ash replacement or a 55% GGBFS replacement was able to reduce expansions in both the modified ASTM C1260 test and the ASTM C1293 test. The modified ASTM C1260 results exhibited expansions below the 0.04% expansion limit at 56 days that was set by Scott and Gress in this modified test. The CPT results , however, indicated that neither the 25% fly ash replacement nor the 55% GGBFS replacement were able to reduce expansions to below the 0.04% expansion limit at two years noted in the ASTM C1293 standard [98]. The results of the CPT can be seen in Figure 1-10.
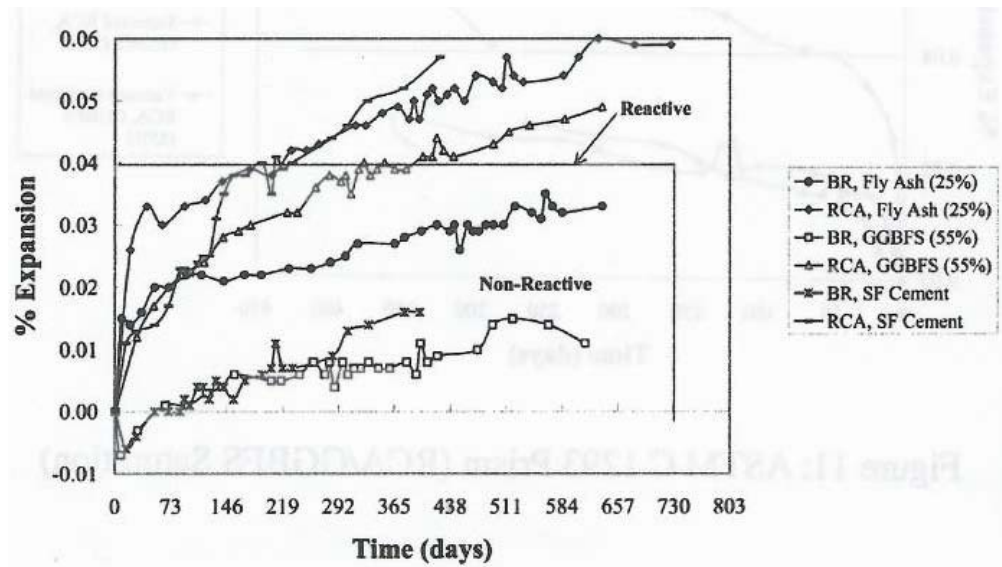
Figure 1-10: Results of CPT tests with SCMS in Scott and Gress [98]

One important observation was that high early expansions were seen in the CPT test results when using the RCA. The RCA was incorporated into the mixture in a dry state. The expansions were attributed to the dry aggregates absorbing water and then swelling, causing expansion of the prism that was not caused by ASR. The tests specimens were then recast using saturated aggregates, and the early age expansions were seen to decrease. However, the RCA used with no mitigation methods still caused expansions above the 0.04% limit at one year [98]. The lithium nitrate was also shown to reduce expansions to within acceptable limits in a modified AMBT test [98].

Also presented in this study was a comparison of expansion results of tests incorporating the RCA and expansions results of the mortar bars containing the quartzite natural aggregate use as the ONA in the RCA. The RCA exhibited higher levels of reactivity than the natural aggregate in the CPT test, and the mitigation methods had less of an effect on the prisms that contained RCA compared to those that contained the natural aggregate [98]. The authors attributed this to a higher amount of available alkalis in the RCA compared to the natural aggregate, because the RCA would contain pre-existing ASR gel and may have been contaminated by de-icing salts, both of which would have increased the alkalis in the concrete compared to the natural aggregates.

A follow-up study was performed using the same materials as those presented in Scott and Gress by Li and Gress [99], however in this study the RCA was used in the standard ASTM C1260 test without removing the adhered mortar. All specimens containing RCA were cast at 100% RCA replacement levels. This study confirmed that replacement levels of SCM had less of an effect on mitigating the ASR in samples containing RCA. The AMBT specimens made with RCA, compared to the AMBT specimens containing only NA, showed less of a reduction in expansion when incorporating fly ash. This study also performed a pore solution analysis to determine the amount of alkalis in the pore solution of the mortar bars, which drives the reaction. The pore solution of the RCA mortar bars and the NA mortar bars had similar amounts of alkalis [99]. This shows that the decrease in effectiveness of the fly ash is not due to an increase in alkalis in the RCA system, but some other mechanism preventing the fly ash from working as effectively.

The most extensive study on applicability of current ASR test methods and mitigation techniques was performed by Shehata et al. This study compared results of the AMBT, CPT and a newer ASR test known at the concrete microbar test (CMBT). This was done in conjunction with testing of mitigation techniques using binary blends of portland cement and silica fume, class F fly ash, class C fly ash, or GGBFS, ternary blends of portland cement and silica fume and class F fly ash, or class C fly ash, or GGBFS [100]. The testing was performed with a single type of RCA, which contained an original reactive siliceous limestone course aggregate known as Spratt. The Spratt aggregate is a widely as a baseline for comparison ASR testing throughout the world. This is because it is petrographically similar to limestones found various regions in the world [89].

The CMBT, described in RILEM TC 191-ARP AAR-5: Rapid Preliminary Screening Test for Carbonate Aggregates [101], is a promising test that is being used to rapidly screen aggregates for alkali-silica reaction. The main advantage of the test is that it uses a larger aggregate size (compared to the AMBT) while still being a rapid test (screening complete in 31 days), this is particularly important to a study on RCA because it maintains the integrity of the RCA particle [100]. This test is currently being used by some researchers to evaluate aggregates, though it has not been approved as an accepted standard in the United States. The test involves casting three 1.6 x 1.6 x 6.3 in. (40 x 40 x 160 mm) prism using an

aggregate gradation between 0.16 and 0.3 in. (4 and 7.6 mm). The prisms are stored in the same environment as used in the AMBT test and measured up to 30 days after submersion in 1 N NaOH. Expansion limits for this test state that any expansions above 0.140% in 30 days indicate potentially deleterious expansions. Shehata et al. modified the CMBT test to use a 1.6 x 1.6 x 11.25 in prism using an aggregate gradation between 0.19 and 0.5 in. [100]

The effect of the crushing (fine versus coarse) on reactivity seen in the CPT caused Shehata et al. to examine the effect of the crushing procedure on reactivity. The authors presented the AMBT results of the RCA after it went through primary crushing, and then after it went through secondary crushing (particles too large for the AMBT test after initial crush were sent through the crusher again to receive the proper gradation) [100]. These results can be seen in Figure 1-11.
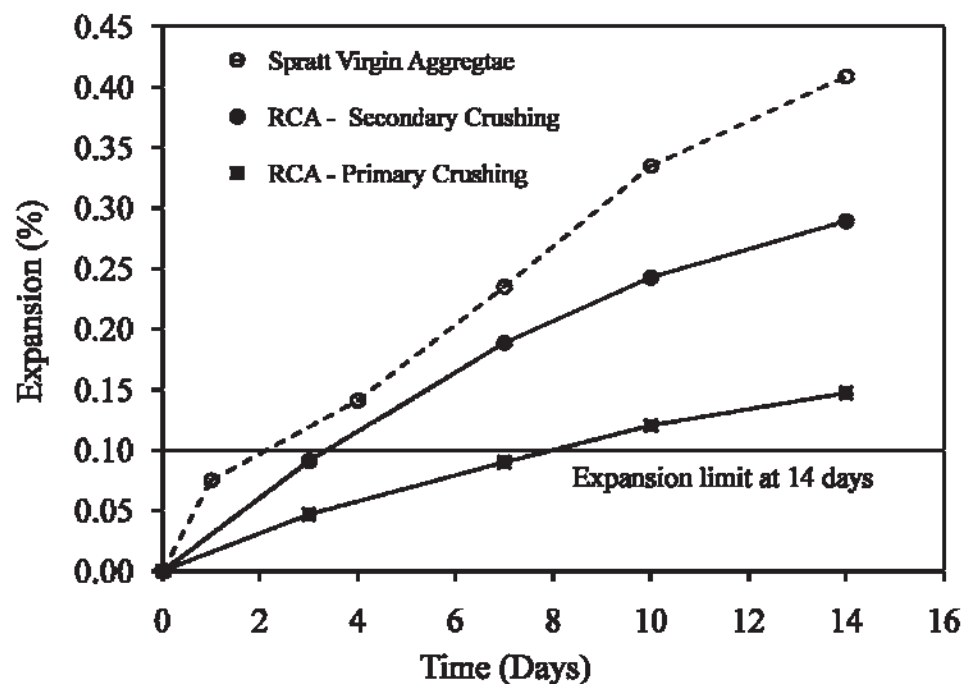
Figure 1-11: Expansions differences in mortar bars made with RCA subjected to different levels of crushing[100]

These results show that particles that undergo primary crushing are less reactive than particles that undergo secondary crushing. The authors contributed this effect to the fact that RCA is a two-phase particle, as it is crushed, the mortar breaks off first. With subsequent crushing of larger particles, there is less mortar to break loose, so the ONAs themselves are then crushed. This results in larger amounts of reactive ONA in the mortar

mixture made with aggregate that underwent secondary crushing (which may occur due to the need for processing), which correlates to the increase in reactivity [100].

The results of tests using mitigation techniques by Shehata et al. also showed that the concrete prisms and mortar bars made with RCA required higher levels of SCMs than was required for the natural aggregate from which it was made, confirming results shown in Scott and Gress [98] and Li and Gress [99]. The results showed that a 50% replacement of portland cement with a class C fly ash was able to control expansions in the prisms containing just ONA but it required a 70% replacement to control expansions in the prisms containing the RCA (comprised of the same ONA source plus adhered mortar). The authors stated that this is generally attributable to three things: additional alkalis contributed to by the adhered mortar, expansion of existing ASR gel in the RCA, and exposing unreacted faces of the original aggregate during crushing procedures of the RCA [100]. The results showed that all the AMBT and CPT correlated well in detecting the potential reactivity of combinations of SCMs and RCA, with the RCA aggregate exhibiting potentially deleterious expansions in both tests [100]. This is exhibited in Figure 1-12.
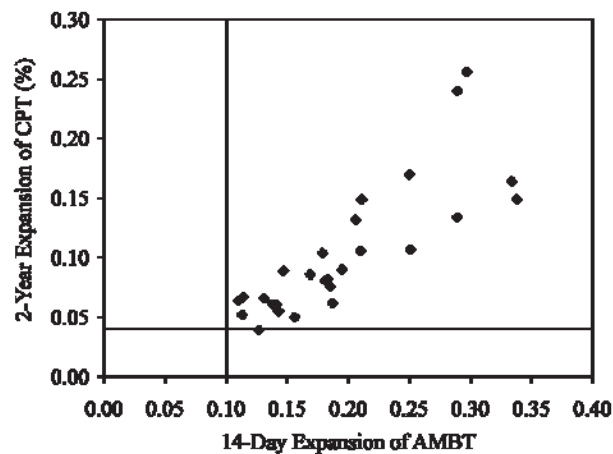
Figure 1-12: Correlation results between AMBT and CPT in Shehata et al. [100]

This graph shows the expansions of concrete prisms at 2 years (1 year for samples not containing SCMs) and 14-day expansions of AMBT mortar bars. The graphs show that there is good correlation between the two, with no mixtures showing conflicting results between the AMBT and CPT tests. One thing to note, though, was that the CPT results of Shehata et al. showed high early expansion results [100], which may be due to the aggregate expansion

described in Scott and Gress [98]. Also of note, was that fine RCA was tested in the CPT as part of this study and shown to cause much less reactivity, though still potentially deleterious, than the coarse RCA [100].

The review presented here on ASR testing of RCA provides a background showing that the current test methods may be acceptable for use in assessing the potential for RCA reactivity. However, it is clear that more research is needed on a wider range of aggregates to assess the overall effectiveness of the tests, as there is some contradiction between the results shown above. There are several points that are clear from the testing completed over the last several years:

- The alkali content of the cement used in testing does have an effect on the overall reactivity seen in the tests; therefore, in future testing cements with similar alkali contents should be used so that comparisons between results can be made;
- RCA may be susceptible to the same pitfalls of correlation between the accelerated mortar bar and concrete prism tests, where the aggregate's results in one test may not always correlate well with results seen in the other; and
- It may take more of a particular mitigation technique when being used with RCA to obtain the same effects seen with natural aggregates, the reasons behind this are not clearly understood, though.

It is important that future testing be completed using the same test methods so that results between research can be correlated. Also important to note is that no testing has been completed yet that correlates the results of ASR testing on RCA to exposure block testing, or field performance. This data is important because it will validate the expansion limit criteria used in the test methods presented above. However, the examination of ASR in concretes made with RCA is still an area of research that is in its infancy, and the collection of all this data will take significant amounts of time and effort.

1.2.6 Mixture Proportioning and Fresh Properties of Concrete Made With Recycled Concrete Aggregates

Due to the high porosity, absorption capacity and variability of RCA, the mixture design can be very important. The mixture design will affect not only the fresh properties: slump, mixture stability, Typically, standard mixture design methods – modified to incorporate the properties of RCA - are used to proportion the amount of fine and coarse aggregate, water, cement, and chemical and mineral admixtures. However, recent research has shown that

there is an alternative mixture design method that can improve the properties of concrete. This alternative mixture design is called the equivalent mortar method, and will be discussed later.

Slump and Stability

Early studies on the slump of concrete made with RCA showed that the incorporation of coarse RCA had little effect on the slump of the RCAC [1, 102]. This was done, however, with w/cm ratios of 0.44 and higher, which could account for a low impact of the RCA on slump. Later studies show that the water demand of the RCA causes the slumps to typically be lower than those found in NAC [23, 28, 37, 49, 50]. An increase in water content of the mixes to correct for RCA's absorption capacity, as well as allowing the aggregates to presoak prior to mixing has been shown to help reduce the slump loss issues seen when using RCA and is suggested in the American Concrete Institute's guide for the "Removal and Reuse of Hardened Concrete" [23]. However, Poon et al. determined that the use of aggregates in the saturated surface dry condition at mixing time had detrimental effects on the hardened properties of the concrete, and showed that air dried aggregates provided a better quality concrete [28]. Additionally, Limbachiya et al. showed that using superplastizer gave acceptable slumps in RCAC without increasing the water content of the mixture [50]. Limbachiya et al. also found that mixtures with RCA exhibited more bleeding and less stability than NAC mixtures, but these issues were also overcome by reducing the water content of the mixture combined with use of a superplasticizer [50].

Density

The density of RCA concrete is slightly lower than that of NAC, which is typically 150 lb/ft^3 for hardened NAC. Density of RCAC was found to be between 125-140 lb/ft^3 (2000-2200 kg/m^3) for fresh concrete and 140-150 lb/ft^3 (2200-2360 kg/m^3)for hardened concrete [22, 23, 37, 49].

Air Content

Hansen reported that the air content of concrete made with recycled concrete aggregate was higher than those of NAC [37]. Jacobsen et al. confirmed this and showed that this was due

to the higher porosity of the recycled concrete aggregate due to the adhered mortar [103]. Limbachiya et al. [50] and Dhir et al. [21] studied the air content stability of RCAC over a duration of time in the mixer and found that the presence of RCA had a negligible effect on the stability of the air content. Dhir et al. also showed that dosage rates of air entraining admixtures are similar to those required for NAC to reach similar air contents [21].

The standard method for testing air content in normal weight concrete is ASTM C231: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method which uses an air pressure meter to measure the air content of the concrete [104]. Jacobsen et al. expressed a concern that the air pressure meter test does not give reliable measurements due to the porosity of the aggregates because the research showed extremely high air contents when using fine RCA [103]. According to the scope of this test, the test method is not applicable for the use of concrete made with aggregates of high porosity [104]. The test method does not, however, state what constitutes a "highly porous aggregate."

Conventional Mixture Design Method

Conventional recycled concrete aggregate mixture designs are very similar to that of natural aggregate concrete. Typical mixture designs involve straight replacement of natural aggregates with recycled concrete aggregates, at varying RCA to NA replacement ratios [19]. Due to the high porosity and lower density of the RCA, lower water to cement ratios and higher cement contents are generally needed to achieve similar compressive strengths to that of NAC [19, 23, 51]. Additionally, due to the high porosity of RCA, it is recommended that water content be adjusted to account for the water that would be absorbed by the aggregates during mixing. Poon et al. showed that this, combined with the use of air dried aggregates, as opposed to saturated surface dry or oven dry aggregates, produced the best strengths as well as had the least amount of slump loss during mixing [28]. Several studies have shown that the use of select supplementary cementitious materials, particularly fly ash, as a replacement for ordinary portland cement can enhance the fresh and hardened properties of concrete, and their inclusion should be considered in any mixture [28, 31, 48, 105]. Suggestions for replacement ratio of RCA to NA in the concrete mixture are few and varied showing a limit of 30-50% coarse RCA content and 20-30% fine RCA content [21, 31, 50, 56]. This is due to the extreme variation in properties between different sources of RCA. The American

Concrete Institute's guide on the "Removal and Reuse of Hardened Concrete" states that "trial mixtures are absolutely mandatory [23]." It is recommended, therefore, that when making RCAC, along with proper classification of RCA themselves, trial batching and mixture design with sample portions of RCA be completed before final selection of mixture design.

Alternative Mixture Design Method

In 2009, an alternative mixture design was proposed by Fathifazl et al. in an attempt to develop a way to prevent the loss of mechanical properties typically seen when NA is replaced by RCA in concrete. The authors state that the reason for the decrease mechanical properties is due to the RCA being a two-phase material, original natural aggregate and adhered mortar. Due to the adhered mortar, when NA is replaced directly mass percentage with RCA, the total mortar (TM) content of the fresh concrete will be higher than that of concrete made with 100% NA. Since the AM has a higher porosity and lower modulus of elasticity, that is what causes the decrease in those properties in new concrete made with RCA [19, 106].

The proposed mixture design by Fathifazl et al. is termed the "Equivalent Mortar Volume Method" (EMV) because the researchers proportion the RCA concrete mixture to have the same TM volume as that of NAC, as well as the same volume percentage of NA (however these natural aggregates would be the original natural aggregates present in the RCA). This mixture design method, however, does not allow for the use of fine RCA. The mixture design method can be seen in [19]. In order to use this design method, the adhered mortar content must be determined. The authors used the method developed by Abbas et al.to determine the adhered mortar content [38, 41]. This method uses a modification of the sulfate soundness test, ASTM C88 to mechanically and chemically remove the adhered mortar from the RCA. The method follows this procedure[38]:

1. Obtain a representative sample of the RCA: ~6.5 lbs (3000g);
2. Oven dry the sample at 221°F (105°C) for 24 hours, then immerse in 26% by weight sodium sulfate solution;
3. While immersed, submit the samples to five freeze-thaw cycles of 17°C for 16 hours followed by 8 hours at 176°F (80°C);

4. Following thaw of the final cycle, drain the solution from the sample and wash with tap water over a No. 4 sieve;

5. Weigh the sample and determine the mass loss to find the percent of adhered mortar that exists on the RCA.

The researchers found that the EMV method produced concrete mixtures containing 100% (nominally) coarse RCA that had higher slump, density, and elastic modulus compared to mixtures made with 100% coarse RCA using the conventional mixture design method and similar water and cement contents; bringing those properties more in line with NAC mixtures [19]. The durability of concrete made with the EMV method was studied by Abbas et al. [107] (working with the same materials as used in [19]); though they only studied the freeze-thaw durability, chloride diffusion, and carbonation depths. The authors found that the freeze-thaw durability was higher than that of RCA made using the conventional method and lower than NAC, though still in an acceptable range. They also found a mixture containing ground granulated blast furnace slag gave the concrete better freeze-thaw resistance. Concerning chloride diffusion in RCA concrete made using the EMV: the EMV method produced better results than the conventional method and were within acceptable ranges. Similar findings were determined for the carbonation depth of the concretes made with RCA using the EMV method over the conventional method [107].

The EMV method shows promise as a way to increase the total replacement level of coarse recycled concrete aggregate without incurring significant losses in mechanical properties of the concrete. The authors, however, only studied the fresh, mechanical and durability properties of concrete using two types of RCA. This method needs to be investigated across a wider range of RCA types to see if the results are reproducible using varied types of RCA. The durability tests also need to be expanded to cover other durability concerns. One area that could be of particular concern is alkali-silica reaction. The use of the EMV method typically results in a higher percentage of the ONA being included in the concrete matrix. If the ONA is a reactive aggregate, this could cause higher expansions in the new concrete.

1.2.7   Summary

This review has both the advantages and disadvantages of using recycled concrete aggregate. RCA presents many difficulties when being incorporated in new concrete, but as shown, most of them can be overcome with alterations to mixture designs or limitations on the

replacement levels of RCA. One of the major obstacles to using RCA, however, is the lack of technical guidance and a general perception of the material as being inferior.

Technical guidance can only be provided once it is understood how to properly classify RCA for use in new concrete. Test methods need to be studied more to determine whether they can be performed on RCA and what benchmarks should be set for the acceptance of different RCAs as a constituent in new concrete. One topic studied in depth as part of this review was how RCA reacts in standard ASR test methods. Existing studies have provided information on how RCA may react in the test but has not been able to provide enough information to ascertain whether the current test methods are applicable to use on RCA. The following two manuscripts will examine the use of RCA in the ASTM C1260, and ASTM C1567 accelerated mortar bar tests.

The goal of the research presented herein is to show whether these test methods can effectively show reactivity across a range of aggregates. The first manuscript will study several different RCAs and how they perform in the ASTM C1260 test. Particularly, it will examine the effect of crushing procedures on the reactivity of the aggregate; and use the results from an interlaboratory study to show the precision of results when RCA is used in the ASTM C1260 test. The second manuscript will focus on mitigation techniques to reduce the expansions caused by reactive RCA. The effect of fly ash, GGBFS, silica fume, and metakaolin blends with portland cement will be examined, and reported on.

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Applicability of the ASTM C1260 Accelerated Mortar Bar Test for Alkali-Silica Reactivity Testing of Recycled Concrete Aggregates

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2. First Manuscript

Applicability of the ASTM C1260 Accelerated Mortar Bar Test for Alkali-Silica Reactivity Testing of Recycled Concrete Aggregates

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Abstract: Using recycled concrete aggregate (RCA) as a replacement for natural aggregate in new concrete is a promising way to increase the overall sustainability of new concrete. This has been hindered, however, by a general perception that RCA is a sub-standard material due to the lack of technical guidance, specifically related to long-term durability, on incorporating RCA into new concrete. The goal of this research project was to determine whether current testing methods (namely ASTM C1260) for assessing natural aggregate susceptibility to alkali-silica reactivity (ASR) could be used to assess the potential reactivity of concrete incorporating RCA. Seven different RCA sources were investigated. It was determined that ASTM C1260 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 to evaluate repeatability and consistency of results. The authors recommend a change to the multi-laboratory precision statements in ASTM C1260, as well as a modification to the mixing and aggregate preparation procedures, when testing the reactivity of RCA using ASTM C 1260.

Keywords: Recycled concrete aggregate, alkali-silica reactivity, sustainable construction

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2.1   Introduction

Over 150 million tons of concrete construction and demolition (C&D) debris is produced each year in the U.S. alone [1, 2]. As the demand for sustainable construction practices increases, more of an emphasis is being placed on recycling the concrete instead of disposing of the material in landfills. Reusing concrete waste as recycled concrete aggregates (RCA) can provide three main environmental benefits: it reduces the amount of debris sent to landfills, decreases the amount of natural aggregates mined from the earth, and it can reduce the amount of transportation required to bring aggregates from a source location to concrete facility. About 66% of the concrete waste in the U.S. is recycled, most of which is used as road base [3]. Only 6% is used as aggregate in new concrete, with the remaining RCA being used as riprap, fill, in hot-mix asphalt or in other applications [3]. Sending concrete demolition waste to landfills also has a significant financial impact on a project. The cost to dispose C&D waste in landfills can be as high as $50 a cubic yard [2], reducing the amount of material sent to the landfill can therefore reduce the costs incurred by the construction industry. Increasing the rate of RCA use in new concrete is imperative to reducing the amount of waste sent to landfills.

RCA is produced by crushing demolished concrete into appropriate gradations for use in civil engineering applications. Large concrete elements are broken up using mobile impact units, which have attachments able to remove reinforcing steel during this initial crushing phase. The rubble is then typically shipped to a large scale crushing facility where it is crushed further into the sizes needed for use in construction. At this phase, magnets can be passed over the crushed material to remove any remaining reinforcing steel in the concrete [4].

A recycled concrete aggregate consists of two phases: the original natural aggregate and the adhered mortar [5]. The original natural aggregate is the coarse aggregate that was used in the creation of the parent concrete. The adhered mortar consists of cement paste and the original natural fine aggregate. The adhered mortar content of RCA increases as the RCA particle size decreases; this is due to weaker components, namely the adhered mortar, breaking off first in crushing operations and being fractured into smaller sizes [6]. In general, the porosity of RCA is higher than that of the natural aggregates, about 10 to 12%

depending on the amount of adhered mortar and aggregate size [7]. Subsequently, the absorption capacity of RCA has been found to be up to 8% higher than natural aggregates [8, 9].

Past work has shown that concrete made with RCA can have up to a 30% reduction in compressive strength [7, 10, 11]. Additionally, reductions in the modulus of elasticity have been noted up to 50% [9, 11, 12]. Further research has shown, however, that when designed properly, concrete made with RCA can actually attain the same or better mechanical properties as concrete made with natural aggregates [13-15]. In order for RCA to be used as a replacement material, new concrete made with it must meet or exceed the current standards for concrete strength and durability. Currently, within the concrete industry, there is a perception that RCA is a substandard building material and this has inhibited its inclusion in concrete mixtures [16, 17]. This can be attributed to a lack of significant research proving the acceptability of RCA as a replacement material for natural aggregate as well as a lack of technical guidance on how to specify RCA for new construction. A study performed in 2003 by the Federal Highway Administration (FHWA) showed that only 11 U.S. state transportation agencies use RCA as a replacement for natural aggregates in new concrete. This study found that the states using RCA in new concrete were particularly concerned about its potential alkali-silica reactivity when used in new concrete [16].

Alkali-silica reaction (ASR) is a leading cause of concrete deterioration worldwide. ASR is the result of a reaction between the alkalis (Na^+ and K^+), hydroxyl ions (OH^-) and reactive silica. In concrete made with natural aggregates, the reactive alkalis are provided mainly by the cement and the reactive silica is present in the aggregates. The RCA may contribute more alkalis to the system than natural aggregates. There may be alkalis in the adhered mortar, or RCA that comes from parent concrete that was exposed to deicing salts may contain higher levels of alkalis than natural aggregates [18]. The presence of alkalis in the pore solution results in a high concentration of hydroxyl ions to maintain charge balance. The hydroxyl ions cause the high pH of the pore solution. The chemical reaction that occurs during ASR causes a gel to form in and around aggregates, and in the surrounding pores in the cement paste matrix. The ASR gel is hygroscopic, and as it absorbs water, it expands. This expansion exerts a tensile force on the surrounding concrete matrix; which, if it exceeds the tensile

capacity of the concrete, can cause cracking. Cracks in the concrete provide a path for more moisture to enter the system, which will cause more expansion of the ASR gel and further cracking. The ingress of moisture into the system can also lead to failure due to other mechanisms such as corrosion or freeze-thaw attack [19].

One of the most common tests to determine if a particular aggregate will cause deleterious expansions due to ASR in new concrete is the ASTM standard C1260: Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Mortar-Bar Method), also known as the Accelerated Mortar Bar Test (AMBT) [20]. However, the use of this test has not been approved for use with RCA. One of the first studies to test RCA using the AMBT method was performed by Shayan and Xu, however they followed the Australian standard RTA T363, which differs slightly from the ASTM C1260 standard, mainly in mortar mixing procedures [21, 22]. This study tested an RCA which contained an original natural basalt/dolerite aggregate. The authors noted that this natural aggregate is known to exhibit potentially deleterious expansions in the AMBT, but performs satisfactorily in the field. The RCA, when tested in the AMBT did exhibit potentially deleterious expansions. However, since the reactive component in the RCA (the original natural basalt/dolerite aggregate) is known to give false results in the AMBT, this information is not suitable for rating the suitability of the AMBT to evaluate the alkali-silica reactivity of RCA.

Li and Gress performed a study that evaluated the alkali-silica reactivity of an RCA that came from a concrete pavement that had deteriorated due to ASR and contained an original natural coarse quartzite aggregate that was known to be reactive [23]. This study indicated that the ASTM C1260 was capable of exhibiting alkali-silica reactivity. The study also compared the expansion results of ASTM C1260 testing for the RCA and the original natural aggregate. These results showed that the RCA had lower levels of reactivity compared to its original natural aggregate [23].

Work by Shehata et al. did seek to understand whether the AMBT would be suitable for use with RCA [24]. The study was performed on RCA that contained a well known reactive original natural silicious limestone coarse aggregate known as Spratt. This study confirmed that the AMBT is capable of determining if RCA is reactive. The authors also observed that

the crushing procedure used to reduce the RCA to the gradation requirements of the AMBT test affected the reactivity of the RCA [24].

From these studies it has been demonstrated that the ASTM C1260 test is capable of detecting aggregate reactivity [21, 23, 24]. It is still unclear, however, if the test can accurately predict the level of reactivity seen in field concrete. Several key pieces of information have still not been elucidated upon:

- the reliability of results when compared to other ASR testing procedures and results from field exposure;
- the reproducibility of results; and
- the effect of crushing procedures on measured reactivity due to change in particle composition during the crushing process.

This research presented herein focuses on the last two topics.

2.2   Research Significance

The purpose of this study was to examine the applicability of the current ASTM C1260 test method to detect RCA reactivity due to ASR. This study was performed in two phases as a multi-laboratory study. The same materials were used in each laboratory so that testing differences occurred only in laboratory equipment and researchers preparing, monitoring and analyzing the samples. Phase I was completed using four laboratory created RCAs. This phase specifically investigated the effects of the crushing procedure on the reactivity of RCA when tested in ASTM C1260. Expansions of mortar bars containing RCA prepared using two different crushing procedures are presented and discussed. Multi-laboratory precision results between four university laboratories are also presented for these four aggregates showing the reproducibility of results across the four laboratories. Phase II was completed with three stockpiled or demolished field structure RCAs to confirm whether the precision results shown in phase I would be comparable to precision results using non-laboratory created RCA. Multi-laboratory precision results between two university laboratories are presented and discussed for these three aggregates. Overall reactivity trends for all seven RCAs used as part of this study are also presented and discussed. This information will provide data on current test methods for ASR when using RCA that will contribute to understanding whether ASTM standards need to be modified to allow the usage of recycled

concrete aggregate. Understanding the reliability of the test methods is essential in allowing their use for new types of aggregates.

2.3 Experimental Investigation

2.3.1 Materials

Aggregates

Seven different recycled concrete aggregates were obtained for this study. Four RCAs, Sp-R, Be-R, Po-R, and Sp-R, were produced from the crushing of outdoor exposure blocks that were used in long-term aggregate alkali-silica reactivity testing and correlation study performed at CANMET, in Ottawa, Ontario, Canada [25, 26]. The exposure blocks were cast under controlled laboratory conditions and measured nominally 15.75 x 15.75 x 28 in. (40 x 40 x 70 cm). The blocks chosen for this study were chosen due to their age, extent of alkali-silica damage, and variation in mineralogy of reactive original natural aggregate. The other RCAs, Ca-R, St-R, and Op-R were chosen to see if testing results would be similar when cast using RCA from unknown parent concrete sources.

Other RCAs were produced by crushing slabs that had been produced from returned concrete at an Oregon, USA ready-mix facility; and from demolished structures that had deteriorated due to ASR in Wyoming, USA. The RCA produced from the ready-mix facility's returned concrete represented a stock piled material, consisting of parent concretes that had different mixture designs and admixtures contained within, the age of the concrete was young though, as the returned concrete slabs were crushed and stored shortly after hardening. The RCA from the structures in Wyoming is from a parent concrete of which little is known, including the type of aggregate, except that it had undergone ASR damage. The various sources of RCA represent a wide range of the potential types of RCA that may be encountered in the field, those with relatively little known information and those with increased amounts of known information. Table 2-1 summarizes the following information concerning RCAs used in this test: RCA source, original natural aggregate type and expansion in ASTM C1260 and ASTM C1293 tests, and absorption capacity of the RCA.

Table 2-1: RCA mineralogy and sources

Recycled Concrete Aggregate	Natural Aggregate Mineralogy	Recycled Concrete Aggregate Origin	Source Type	Natural Aggregate Mortar Bar Expansion in ASTM C1260 Test (14 d exp. %)	Aggregate Concrete Prism Expansion in ASTM C1293 Test (1-year exp %)	Abs. Capacity of Recycled Concrete Aggregate (%)
Al-R	Mixed mineralogy gravel (CA)	Exposure block from Ontario, CA	Laboratory created	0.36	0.09	6.66
Be-R	Argillaceous limestone (CA)	Exposure block from Ontario, CA	Laboratory created	0.17	0.04	6.18
Po-R	Sandstone (CA)	Exposure block from Ontario, CA	Laboratory created	0.09	0.13	4.22
Sp-R	Greywacke (CA)	Exposure block from Ontario, CA	Laboratory created	0.46	0.22	7.78
Ca-R	Silicious river gravel (CA and FA)	Returned concrete stockpile at Oregon readymix facility	Stockpile	FA: 0.81 CA: 0.59	Unknown	9.32
St-R	Unknown	ASR affected stairs in Wyoming	Field structure	Unknown	Unknown	3.01
Op-R	Uknown	ASR affected foundation in Wyoming	Field structure	Unknown	Unknown	3.62

Cement

An ASTM C150 type I/II portland cement with high alkali (HA) content, Na_2O_{eq} of 0.91, was used in this study. All laboratories used the same cement for the multi-laboratory study. Table 2-2 shows the oxide analysis for this cement.

Table 2-2: Cement oxide analysis

Oxide	Oxide Short	Type I/II HA 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_{eq}	0.91
Sulfur Trioxide	SO_3	3.32
Loss on Ignition		2.82

2.3.2 Procedures

The ASTM C1260 test method was used in this study to assess the alkali-silica reactivity of the selected RCAs. According to ASTM C1260, mortar prisms that measure 1 x 1 x 11.25 in. (25 x 25 x 285 mm) were cast at a fine aggregate to cement ratio of 2.75:1 and a w/cm of 0.47. A stainless steel gage stud was cast into both ends of each bar to provide an effective 10.00 ± 0.10 in. (254 ± 2.54 mm) gage length. After curing for 24 ± 2h in 95% or higher relative humidity and 73 ± 3°F (23 ± 2°C), the mortar bars were submerged in tap water and placed in a 176 ± 3.6°F (80 ± 3.6°C) oven where they equilibrated before the next reading. The initial, or zero, reading of the bars was taken 24 ± 2h later and the bars were quickly transferred to a solution of 1 N NaOH which was already at 176 ± 3.6°F (80 ± 3.6°C). The bars then remained in 1 N NaOH at 176 ± 3.6°F (80 ± 3.6°C) for a period of 28 days [20]. Several measurements were taken throughout this time period at approximately the same time each day. For this study, length measurements were taken at 0, 1, 3, 5, 7, 10, 12, 14, 17, 21, 24, and 28 days. Length change was recorded to the nearest 0.0001 in. (0.0025 mm) and results are presented for the average of three prisms to the nearest 0.01% per ASTM C 1260.

Expansion criteria for this test fall into three categories within ASTM C1260 based on expansion measured 16 days after casting (14 days after immersion in 1 N NaOH). Expansions of less than 0.10% are generally considered to be indicative of innocuous behavior. Expansions of more than 0.20% indicate that the aggregates are potentially deleterious. Expansions that fall between 0.10 and 0.20% indicate that the aggregate may exhibit either innocuous or deleterious performance in the field [20]. The above expansion criteria, as described in ASTM C1260, are not actually used by many researchers or agencies, but rather, many ASR researchers and engineers use an expansion limit of 0.10% after 14 days of immersion in the soak solution to indicate aggregate reactivity [27]. Some testing agencies and researchers monitor the specimens longer, often up to 28 days after initial submersion in the 1 N NaOH solution, with continued periodic measurements. However, research has shown that using the 0.10% expansions limit at 28-days after immersion does not correlate well with field performance, some aggregates will be considered as "potentially deleterious" when they actually perform satisfactorily in the field [27]. Expansions are shown here to 28 days for informational purposes only. The 14-day expansion criteria is used to evaluate the reactivity of the RCA used in this study. The multi-laboratory precision for this test states that, for expansions greater than 0.1%, the average coefficient of variation is 15.2% at 14 days after submersion in 1 N NaOH, and the difference between tests conducted in different laboratories should not exceed 43% from the mean expansion [20] for natural aggregates.

Aggregate Preparation

The ASTM C1260 test is a mortar bar test and requires the aggregate to be a specific fine aggregate gradation [20]. The gradation requirements can be seen in Table 2-3.

Table 2-3: Aggregate gradation requirements

| Sieve Size | | Mass % |
Retained On	Passing	Retained
0.0937 in. 2.36 mm (No. 8)	0.157 in. 4.75 mm (No. 4)	10
0.0469 in. 1.18 mm (No. 16)	0.0937 in. 2.36 mm (No. 8)	25
0.0234 in. 600 µm (No. 30)	0.0469 in. 1.18 mm (No. 16)	25
0.0117 in. 300 µm (No. 50)	0.0234 in. 600 µm (No. 30)	25
0.0059 in. 150 µm (No. 100)	0.0117 in. 300 µm (No. 50)	15

The RCA must be crushed using mechanical methods to reach this gradation. The parent concretes were first broken up on site using large mechanical means to, nominally, 4 to 6 in. (10 to 15 cm) diameter pieces. These were then brought to a pilot-scale crushing facility which reduced the materials to, nominally, 0.005 to 0.75 in. (0.127 to 19 mm) diameter pieces. If required, this was then further crushed using laboratory scale crushing machines to the appropriate gradation for the ASTM C1260 test.

Gress and Kozikowski speculated that using the ASTM C1260 grading required aggregate crushing that is too aggressive because it can destroy the integrity of the two-phase RCA particle (original natural aggregate and adhered mortar), and thus alter its reactivity [28]. Work by Shehata et al. also evaluated this problem by performing ASTM C1260 testing on RCA that had gone through one level of crushing, and then a second set of testing on RCA that had been left over from the first crushing (slightly larger particles) and crushed again; that study found that the amount of crushing can have a signficant impact on the reactivity

of aggregates [24], which was attributed to the loss of adhered mortar during successive crushing [6]. To investigate this, material from the crushing facility produced from the four exposure blocks from Ottawa, Ontario, Canada (i.e. aggregates labeled Al-R, Be-R, Po-R , and Sp-R) that met the ASTM C1260 gradations (i.e. < 0.157 in. (4 mm)) was put aside and labeled as "crusher's fines" (CF). The larger material (i.e. > 0.157 in. (4mm)) produced from the pilot scale crushing was then re-crushed using laboratory crushers to the appropriate gradation for the ASTM C1260 and labeled "re-crushed" (RC). These two materials were then tested separately as part of the multi-laboratory study. Generally, the CF were observed (visually) to have a high adhered mortar content, whereas the RC aggregate had a more even distribution of adhered mortar and original natural aggregate. The adhered mortar content of the RCA for use in the ASTM C1260 test was unable to be determined. A method to determine the adhered mortar content of an RCA was developed by Abbas et al., however this method is only applicable for use with aggregates greater in size than 0.187 in (4.75 mm) [29]. No method has been developed to determine the residual mortar content of fine RCA. The three aggregates used in phase II, Ca-R, St-R, and Op-R, were evaluated using only the re-crushed material.

Aggregate Washing

Previous researchers have speculated that washing aggregates may result in a reduction in expansion due to washing away available alkalis [23, 24]. However, ASTM C1260 states that aggregates that need to be crushed to meet the gradation requirements must be washed free of dust and fine particles, and then dried prior to use [20]. This is typically done by placing the crushed aggregate over a sieve of a finer mesh size than the gradation, and spraying with tap water until the water that passes through the aggregate runs clear. It was necessary to modify the aggregate washing procedure prior to incorporating RCA in to sample mixtures. When doing this with the RCA, it was found that the water never ran clear. A prolonged washing period may alter the characteristics of the RCA by eroding away adhered mortar, hydrate unhydrated cement particles in the RCA, wash away (e.g. leach) calcium or alkalis from the RCA, or washing away existing ASR gel within the RCA. In order to counter these effects, but still provide a basic level of washing for the aggregate, an alternate procedure was adopted as follows:

- Sieve each aggregate, and keep separated according to each fraction retained on sieve sizes;
- Measure out about 3.5 lbs (1600 g) of material onto a fine sieve;
- Wash aggregate using a rubber hose with a fanned-spray hose nozzle for the following times 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 aggregate into a 230 °F (132 °C) oven to dry for 24 ± 2 hours before using.

Absorption Capacity

As noted earlier, the absorption capacity of RCA has been shown to be significantly higher than virgin aggregate, depending on the composition of the RCA, ranging from 3 to 12% [8, 9]. The standard test method for determining the absorption capacity of aggregates, ASTM C128, is not currently approved for use with RCA [30], because it states a soak time of 24 ± 4 hours is required to reach full saturation. This soak time may not be valid for aggregates with high absorption capacities. In order to find the appropriate soak time for RCA, a laboratory-created RCA was soaked for 24, 48, and 72 hours. The absorption capacity was checked for each soak time, and it was determined that 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. Furthermore a soak time of only 30 minutes was required to reach 85% of the total absorption capacity of the aggregate. It was determined that the ASTM C128 method's 24 hour soak period could be used to determine the absorption capacity of the RCA. The absorption capacity of the RCA used in this study can be seen in .

Mortar-Bar Mixing Procedure

Previous work by Scott and Gress using the concrete prism test (ASTM C1293) has shown that using RCA in the oven dry state in ASR testing could result in early expansion of the test specimens. This is thought to be because the highly absorptive RCA takes in water from the concrete matrix and swells. It was shown that presoaking aggregates prior to running the ASR tests produced less early expansion [18]. Also, the high absorption capacity can result in a significant reduction in workability when using RCA [31]. Therefore, it was decided that

the RCA should be soaked in the mixing water, with an adjustment to account for the absorption capacity of the aggregates. The RCA was soaked for 30 minutes, to allow for 85% of the absorption capacity of the RCA to be absorbed, prior to use in the ASTM C1260 test. This was determined based on the absorption rate of the RCA.

ASTM C1260 states that the mixing procedure for casting the mortar bars should follow ASTM standard C305 [20]. This standard states that the mixing water be placed in the bottom of a 1.25 gal. (4.73 liter) three speed commercial mixer, with the cement placed on top. This then soaks for 30 seconds prior to mixing in the aggregate [32]. Due to this, the mixing procedure needed to be modified to accommodate the presoaking of the RCA. The modified mixing procedure is shown as follows:

- After washing and drying the aggregates, 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 and 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 this work was performed in two phases. Phase I included the four laboratory multi-laboratory study. This phase of the study used the Al-R, Be-R, Po-R, and Sp-R RCA. In order to examine the effects of crushing procedure, different mixtures were cast using the CF and the RC versions of this RCA. Specimens with 100% RCA, 50% RCA and 25% RCA were cast for both the CF and RC with non-reactive natural sand (i.e. expansions below 0.10% in the ASTM C1260 test) used for the remaining portion of the material required for the mixtures. This phase also provided the data, from the multi-laboratory study, to assess the test's repeatability and applicability of the precision statements listed in ASTM C1260. The number of ASTM C1260 mortar bar sets cast by each laboratory in Phase I can be seen in Table 2-4.

Table 2-4: Multi-laboratory mortar bar sets (each set composed of 3 bars) for Phase I

Crusher's Fines RCA				
Mixture Type (% Replacement of NA by RCA)	Po-R	Sp-R	Be-R	Al-R
100% RCA	1	2	1	1
50% RCA	1	1	2	2
25% RCA	1	1	1	2
Re-crushed RCA				
Mixture Type (% Replacement of NA by RCA)	Po-R	Sp-R	Be-R	Al-R
100% RCA	1	3	1	1
50% RCA	1	1	2	2
25% RCA	1	1	1	2

Phase II involved further ASR testing of RCA in a second, two laboratory, multi-laboratory study using the Ca-R, St-R, and Op-R RCAs, to determine if stockpiled and field structure sourced RCA produced similar results and repeatability as those produced by the laboratory aggregates. Specimens with 100% RCA, 50% RCA, and 25% RCA replacement levels were cast using the Ca-R RCA; and specimens with 100% RCA, 50% RCA, and 20% RCA replacement levels were cast using the St-R and Op-R RCAs. The number of ASTM C1260 mortar bar sets cast by each laboratory in Phase II can be seen in Table 2-5.

Table 2-5: Multi-laboratory mortar bar sets (each set composed of 3 bars) for Phase II

Mixture Type (% Replacement of NA by RCA)	Ca-R	Sp-R	Be-R
100% RCA	2	2	1
50% RCA	2	2	2
25% RCA	2	N/A	N/A
20% RCA	N/A	2	2

The naming convention for mortar mixtures used in this study is as follows: original natural aggregate name – recycled (R) or virgin (V) – replacement level (for RCAs only) – crusher's fines (CF) or re-crushed (RC). Thus, for an RCA whose original natural aggregate Be, at a

25% replacement level using the crusher's fines, the mixture name will appear as "Be-R-25-CF".

2.4   Results

Figure 2-1 and Figure 2-2 show the expansion of mortar specimens up to 28 days for the crusher's fines RCA and re-crushed RCA, respectively, at a 100% replacement level for the Al-R, Be-R, Po-R and Sp-R aggregates for specimens cast at the Oregon State University laboratory only.
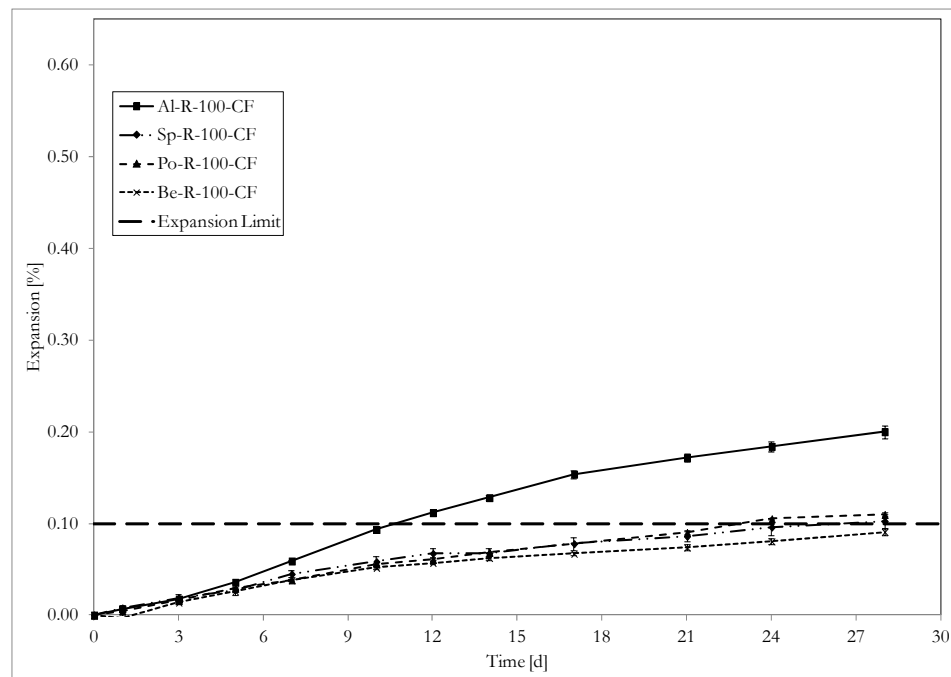

Figure 2-1: Expansion as a function of time for 100% replacement level of RCA using crusher's fine (Oregon State University Laboratory specimens only)
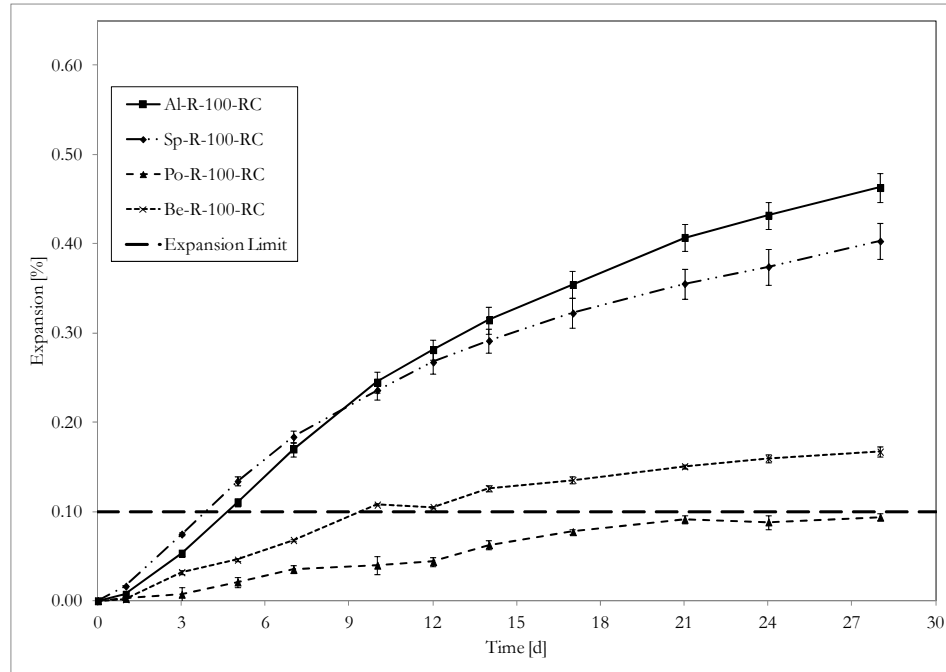
Figure 2-2: Expansion as a function of time for 100% replacement level of RCA using re-crushed (Oregon State University Laboratory specimens only)

The Al-R-100-CF is the only sample set to exceed the expansion criteria of 0.10% for the all four of the crusher's fines RCAs, classifying it as potentially deleterious according to ASTM C1260. The Po-R-100-CF and Sp-R-100-CF sample sets do exceed the 0.10% expansion limit at day 28; however this does not change their classification according to the standard used as part of this study. When using the re-crushed material there are three sample sets that exceed the expansion criteria, Al-R-100-RC and Sp-R-100-RC, and Be-R-100-RC. Of all the RCAs, Po-R was the only set that exhibited less expansion when made with re-crushed aggregate. Al-R, Sp-R, and Be-R showed increased expansion using the re-crushed aggregate. It should be noted that the original natural aggregate used in the Po-R is a siliceous sandstone (see) that generates low expansion in the ASTM C1260 test. This is due to the crushing process that can reduce or eliminate the reactive siliceous phase from the size fractions used for mortar bar testing [33].

Figure 2-3 presents the 14-day expansions (average of three bars at each of four laboratories) across all specimens made as part of the multi-laboratory study for Al-R, Sp-R, Po-R, and Be-R RCAs at all three replacement levels: 25%, 50% and 100%.
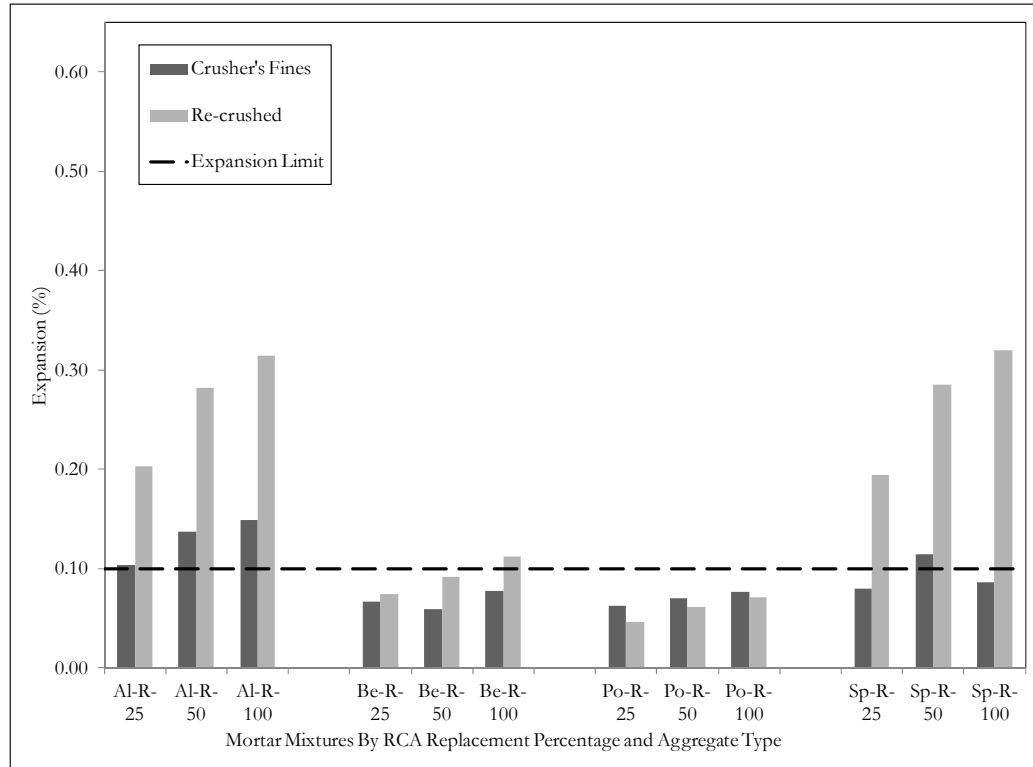
Figure 2-3: Average expansion at 14 days for all re-crushed and crusher's fines sample sets using the Al-R, Be-R, Po-R, and Sp-R RCAS

These results also show that there are generally higher expansion levels for the re-crushed material, except for the Po-R aggregate. The Sp-R and Al-R show significantly higher expansions in the re-crushed RCA sets (over 100% increase in expansion at 100% replacement levels for both aggregates). There is also a general trend that higher replacement levels produce higher expansions for both the crusher's fines and the re-crushed; though there are exceptions to this in the crusher's fines sets, particularly the Be-R-50-CF and Sp-R-50-CF sets. Also observed is that, for all four aggregates shown, the expansion increase between different levels of processing decreases as the aggregate replacement level decreases.

Table 2-6 shows the mean expansions, the coefficients of variation, the precision boundary (43% above or below the mean expansions according to ASTM C1260 for natural aggregate) and number of outliers from the precision boundary for each RCA replacement levels and aggregate type used in Phase I of this study for the crusher's fines and re-crushed fines.

Table 2-6: Multi-laboratory expansion averages, coefficients of variation, and precision limits and outliers for phase I RCAs

Crusher's fines Al-R, Sp-R, Po-R, and Be-R 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
Al-R-25-CF	24	0.10	19.0	0.059	0.147	0
Al-R-50-CF	24	0.14	27.6	0.078	0.196	1
Al-R-100-CF	12	0.15	21.1	0.085	0.213	0
Be-R-25-CF	12	0.07	20.5	0.038	0.095	0
Be-R-50-CF	24	0.06	21.0	0.034	0.084	0
Be-R-100-CF	12	0.08	16.9	0.044	0.111	0
Po-R-25-CF	12	0.06	22.9	0.036	0.089	0
Po-R-50-CF	12	0.07	13.1	0.040	0.101	0
Po-R-100-CF	12	0.08	10.8	0.043	0.109	0
Sp-R-25-CF	12	0.08	22.2	0.045	0.114	0
Sp-R-50-CF	12	0.11	27.1	0.065	0.163	0
Sp-R-100-CF	24	0.09	26.8	0.049	0.123	0
Re-Crushed Al-R, Sp-R, Po-R, and Be-R 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
Al-R-25-RC	24	0.20	11.5	0.116	0.291	0
Al-R-50-RC	24	0.28	11.5	0.161	0.403	0
Al-R-100-RC	12	0.31	5.8	0.179	0.450	0
Be-R-25-RC	12	0.08	22.8	0.043	0.107	0
Be-R-50-RC	24	0.09	8.5	0.052	0.131	0
Be-R-100-RC	12	0.11	17.5	0.064	0.161	0
Po-R-25-RC	12	0.05	27.5	0.026	0.066	0
Po-R-50-RC	12	0.06	7.3	0.035	0.088	0
Po-R-100-RC	12	0.07	10.4	0.040	0.101	0
Sp-R-25-RC	12	0.20	16.5	0.111	0.278	0
Sp-R-50-RC	12	0.29	7.9	0.162	0.407	0
Sp-R-100-RC	36	0.32	20.2	0.182	0.457	0

All but one sample set fell within the 43% multi-laboratory precision boundary limits according to the ASTM C1260, which was one of the Al-R-50-CF sets. The coefficient of variation (COV) for this group of results varied greatly, however. The sample sets cast with the crusher's fines showed multi-laboratory COVs that varied from 10.8% to 27.6%. The sample sets cast with the re-crushed material showed multi-laboratory COVs that varied from 5.8% to 22.8%. The highest multi-laboratory COV was for the Al-R-50-CF at 27.6%, which also corresponds to the only outlier for the multi-laboratory precision boundary.

Figure 2-4 shows the expansion of mortar specimens up to 28 days for the crusher's fines RCA and re-crushed RCA, respectively, at a 100% replacement level for the Ca-R, St-R, and Op-R aggregates for sample sets cast at the Oregon State University laboratory only.
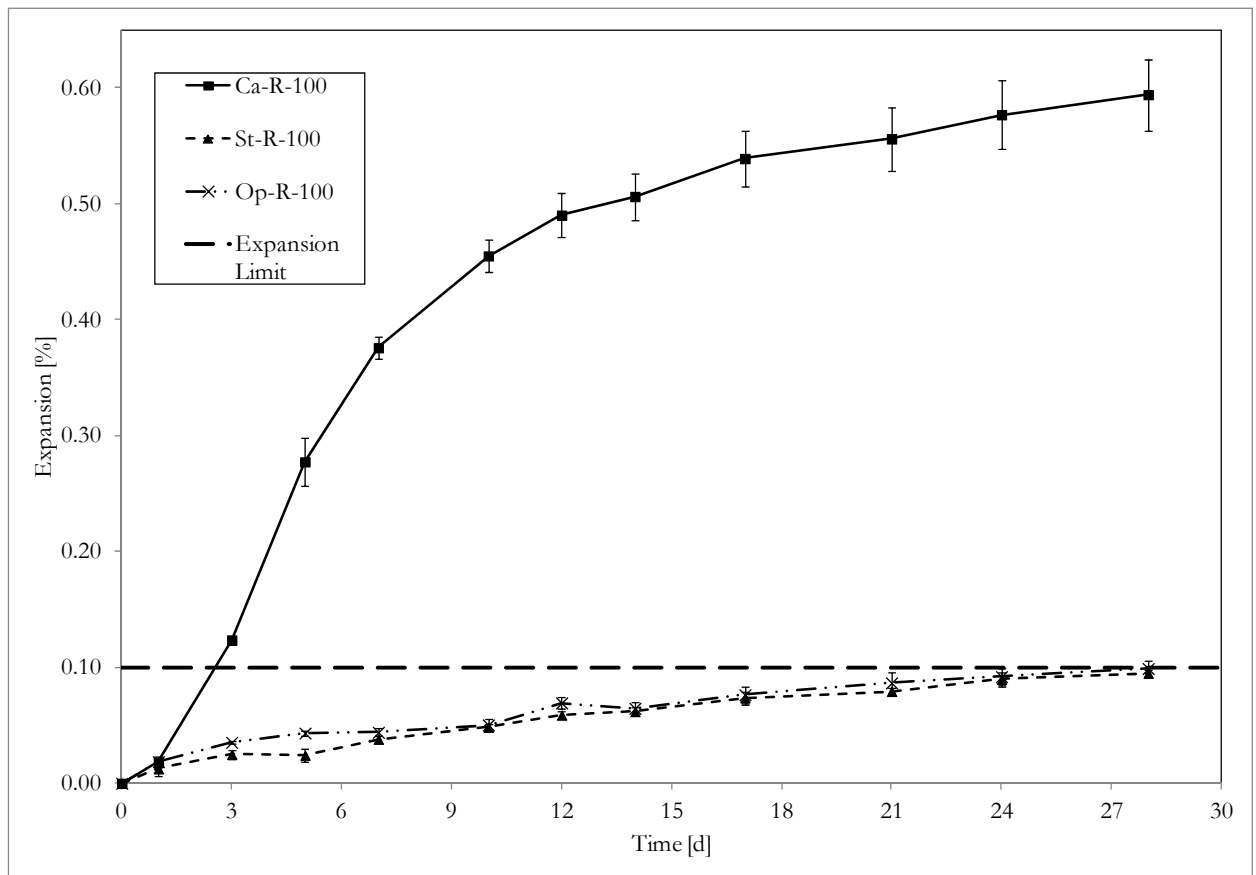

Figure 2-4: Expansion as a function of time for 100% replacement level of RCA using Ca-R, St-R, and Op-R RCAs (Oregon State University Laboratory specimens only)

Of the aggregates tested as part of Phase II, the Ca-R-100 was the only one to present as reactive enough to cause potentially deleterious expansions according to the ASTM C1260 14-day expansion limit. Neither the St-R-100 nor the Op-R-100 exceeded this limit; they did not exceed the 0.10% expansion limit, even at 28 days of testing. The Ca-R-100 also caused significantly more expansion than either than either the St-R-100 and Op-R-100 specimens.

Table 2-7 shows the mean expansions, the coefficients of variation, the precision boundary (43% above or below the mean expansions according to ASTM C1260) and number of outliers from the precision boundary for each RCA replacement levels and aggregate type used in Phase II of this study.

Table 2-7: Multi-laboratory expansion averages, coefficients of variation, and precision limits and outliers for phase II RCAs

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
Ca-R-25	12	0.28	3.4	0.16	0.40	0
Ca-R-50	12	0.44	3.3	0.25	0.63	0
Ca-R-100	12	0.50	3.8	0.29	0.72	0
St-R-20	12	0.08	8.7	0.04	0.11	0
St-R-50	12	0.07	14.3	0.04	0.10	0
St-R-100	12	0.06	4.6	0.04	0.09	0
Op-R-20	12	0.07	7.7	0.04	0.10	0
Op-R-50	12	0.06	3.0	0.03	0.08	0
Op-R-100	9	0.05	14.2	0.03	0.08	0

The COVs for this set of aggregates ranged from 3.0% to 14.3%, which is within the 15.2% COV limit for the ASTM C1260 test. Also, all sample sets fell within the precision boundary limits (43% above or below mean expansion in ASTM C1260) for their respective aggregate type and replacement levels.

Figure 2-5 shows the average 14 day expansions for all different RCAs used in this study.
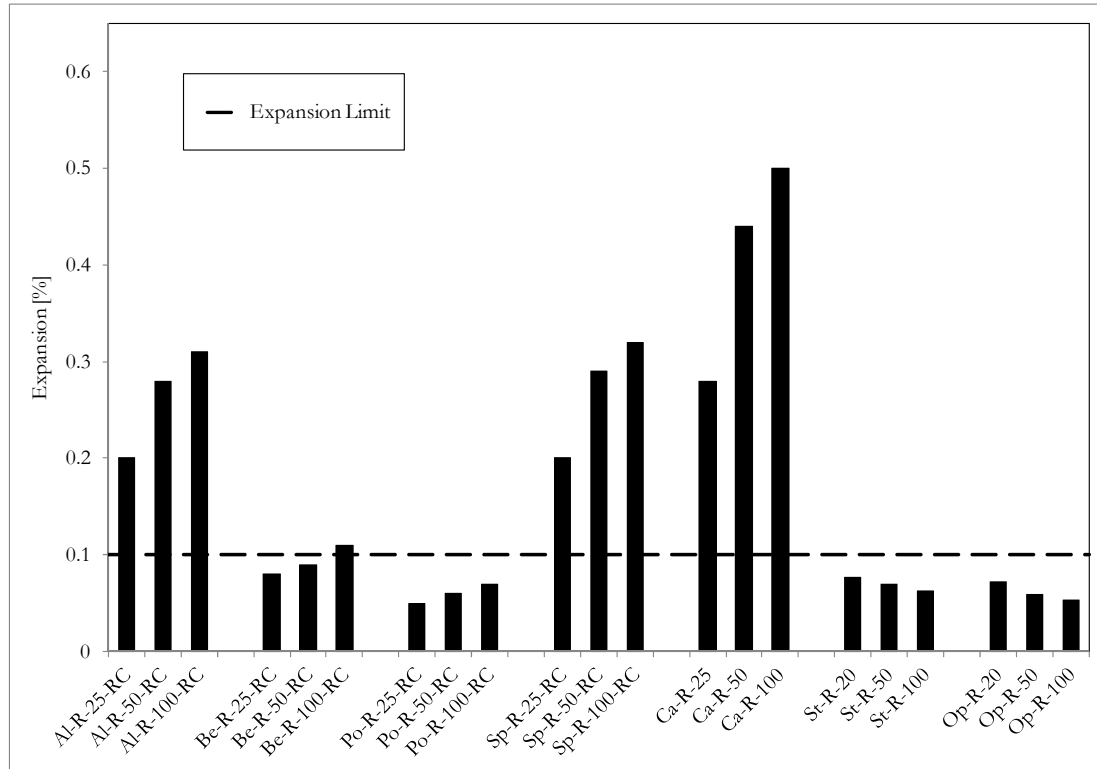
Figure 2-5: Average expansions for at 14 days for all RCAs

Only re-crushed material from phase I aggregates is displayed here because they were processed similarly to those aggregates used in phase II. These results show that expansion is highly varied and dependent on aggregate type and RCA replacement level. Also observed is that, for all aggregates except the two produced from field structures in Wyoming (St-R and Op-R), the higher replacement levels produce higher expansions. The St-R and Op-R, however, show an opposing trend to this: higher replacement levels produce lower expansions. When comparing the ASTM C1260 14 day average expansions for the mortar bars made with RCAs shown in with the corresponding original natural aggregate mortar bar expansions listed in , it is observed that no RCA causes greater expansions than its original natural aggregate in the ASTM C1260 test.

2.5   Discussion

The data presented here confirmed results that have been seen in previous work [21, 23, 24] that the ASTM C1260 testing method is able to detect reactivity of RCA by measuring

expansions in mortar bars in which the RCA is incorporated. The data showed that the amount of reactivity is significantly affected by:

- The crushing procedure used to reduce the RCA to the appropriate gradation for the ASTM C1260;
- The amount of RCA incorporated into the mixture; and
- The reactivity of the original natural aggregate.

 shows that the crushing procedure has a significant impact on the level of expansion seen in the ASTM C1260 test. This can be attributed to a reduction in adhered mortar that occurs during the crushing process. As a recycled concrete aggregate goes through successive crushing, the adhered mortar is more likely to be crushed off first, leaving higher percentages of original natural aggregate content in the RCA [6]. An extra level of crushing caused the re-crushed aggregate to have a higher original natural aggregate content compared to the crusher's fines, which provided more reactive aggregate. Subsequently the mortar bars made with re-crushed material had higher expansions than those made with the crusher's fines. It has also been shown that RCA's adhered mortar content increases inversely with aggregate size [6]. Therefore, using the re-crushed material in the ASTM C1260 will be more representative of coarse RCA used in new concrete.

A general trend observed in expansions of the mortar bars presented here is that expansion increases as their RCA replacement levels increase (from 20 or 25 to 50 to 100%). This increase in expansion can be attributed to similar reasons as those that caused more expansion due to the re-crushed RCA when compared to crusher's fines RCA: as more RCA is included in the mixture of the mortar bar, more of the reactive original natural aggregate is also included in the mortar bar. This observation is consistent for most of the presented RCAs, however the St-R and the Op-R aggregates do not follow this trend. This could be due to two reasons: the age of the parent concrete or the the 20% replacement levels actually created a pessimum effect.

Though the expansions of these two aggregates decrease as the replacement amount increases the difference in expansion is not significantly different (a difference of 0.01% between each replacement level for both aggregates). This suggests the reactivity difference compared to the other aggregates may be caused by a lack of available reactive materials. The

field structures which were the parent concrete for St-R and Op-R were older at the time of removal from service than the exposure blocks and the returned concrete slabs were at the time of their demolition. The longer time span allows for more time for the alkali-silica reaction to occur. This may have depleted some of the available reactive silica in the original natural aggregates, leaving less reactive silica in the aggregate to react in the ASTM C1260 test.

Alternately, the inverse relationship between expansion and RCA replacement level seen in the St-R and Op-R could be due to a pessimum effect. Some aggregates are known to have pessimum effects where up to a certain percentage of reactive material, expansions increase, however beyond that level, expansions decrease [34-36]. This indicates an ideal balance between reactive silica and available alkali that will produce the highest expansion. These aggregates could be exhibiting higher expansions at lower replacement levels. Neither RCA, however, exceeded the ASTM C1260 expansion limit of 0.1% at 14 days after submersion in 1 N NaOH solution. Further testing and petrographic examination of the RCAs, and mortar bars, should be performed to confirm the contradictory trend seen in the St-R and Op-R aggregates compared with the other aggregates. When RCA is used in new concrete, it is often used as a partial replacement for natural aggregate, typically recommended to be limited to 30 to 50% coarse RCA or 20 to 30% fine RCA [10, 21, 37]. This differing trend shows that, at all replacement levels, testing is required to ensure that the reactivity of the RCA is characterized accurately.

The highest average expansions exhibited in this study are from the mortar bars made with the Ca-R aggregate, at a 100% RCA replacement. These mortar bars had average expansion of 0.5%. The main reactive component of RCA is provided by the original natural aggregate. The original natural aggregate for the Ca-R has the highest expansion in the ASTM C1260 test compared to all the other known expansions for the original natural aggregates used in the creation of the RCA parent concretes used in this study. Additionally, the Ca-R aggregate contained both a reactive original natural fine, and original natural coarse aggregate. All of the RCAs produced from the laboratory cast exposure blocks were made with only an original natural coarse aggregate. The Ca-R would contain more reactive material in it comparatively because there would be reactive material in both the adhered mortar and the

original natural aggregate. All of the RCAs with original natural aggregates that caused expansions exceeding the ASTM C1260 14-day expansion limit of 0.10%, also resulted in expansions that exceeded the ASTM C1260 expansion limit. It is important to note, however, that this may not always be the case, particularly if, as explained above, a pessimum proportion exists for a particular aggregate.

Important to note is that this set of results is true for the ASTM C1260 testing environment only. Further research needs to be completed to correlate the results presented here with other tests, particularly the ASTM C1293 test (also known as the concrete prism test (CPT)) [38] which is widely regarded as the best test for determining whether reactive aggregates will cause deleterious expansions in the field. These results should also be correlated with outdoor exposure block testing and field performance, as the ASTM C1293 test has not yet been accepted as a valid test method for evaluating the reactivity of RCA. This correlation is important because the two tests, ASTM C1260 and C1293, can sometimes produce conflicting results [25-27]. The ASTM C1260 test is often preferred, though, because it can be completed in 16 days, whereas the ASTM C1293 test requires a year-long testing program.

Shayan and Xu [21] performed ASTM C1260 and C1293 testing on an RCA with a original natural aggregate with a basalt/dolerite mineralogy. The RCA presented as reactive according to the ASTM C1260 14-day expansion limits, however in the ASTM C1293 test the prisms did not exceed the expansion limit (0.04% at 1 year). This particular original natural aggregate was, however, known to react dissimilarly in the ASTM C1260 and C1293 tests. Research by Shehata et al. [24] has shown that testing performed on RCA can exhibit good correlation between the ASTM C1260 and C1293 tests. However, this testing was performed on only a single RCA and cannot be assumed to be indicative of RCA as a material. It is important to note that the testing limits used (both as part of this study and in [21, 24]) are based off of correlations between testing and field performance using natural aggregates. Further research with outdoor exposure block testing and field performance correlation needs to be completed to understand if these expansion limits can be applied to RCA.

All but one of the specimen sets presented in this study exceeded the multi-laboratory precision boundary limits of 43% set by ASTM C1260 (and). This set, one of the Al-R-50-CF sets, corresponded to the highest COV exhibited by all mortar bar sets presented, which was 27.6%. The multi-laboratory COV limit set by the ASTM C1260 standard, 15.2%, does not seem to correlate well with Al-R, Sp-R, Po-R, and Be-R aggregates. Several of these sample sets exhibited COVs higher than 15.2%. The crusher's fines sets had a significantly higher average COV than that of the re-crushed RCA. This difference may be attributed to the crushing process, which produces a more uniform aggregate through the re-crushing process than that which is received in the crusher's fines. The stockpile and field structure RCAs precision correlated well with those of the RCA of laboratory created parent concretes. None of the Ca-R, St-R, or Op-R sets exceeded the precision boundary limits prescribed by the ASTM C1260 test. They also were all within the 15.2% COV limits; this may be because these were only tested in two laboratories, whereas the set tested in phase I was tested in four laboratories which allowed room for further variation. From these results it can be concluded that the precision boundary limits for multi-laboratory testing are acceptable for testing recycled concrete aggregate based on the results of this study, however the COV may need to be broadened due to the nature of RCA. Further testing using different RCA and more laboratories should be performed to confirm these results.

2.6   Conclusion

The results presented from this study of RCA have shown that the ASTM C1260 test can be used to assess the potential alkali-silica reactivity of recycled concrete aggregates. The following conclusions were made based on the results presented in this research:

- The absorption capacity testing, using ASTM standard C128 methods, required a 24-hour soaking period to reach 95% of the RCA's total absorption capacity. Additionally, the RCA reached 85% of its total absorption in 30 minutes.

- Modifications to the standard mixing procedure are required to properly mix mortars containing RCA. Modifications include an addition of a 30 minute soaking period in the mixing water for the aggregates prior to mixing due to the high absorption capacity of RCA, and possibility of aggregate swelling.

- Increased amounts of crushing of the RCA will provide more access to original natural aggregates resulting in higher expansions than RCA that is tested with less crushing.

- The precision statement used in the ASTM C1260 for multi-laboratory testing is acceptable based on the results shown here, however the coefficient of variation may need to be modified to apply to RCA.

Further testing is required to confirm the precision statement results presented here. Additionally, further testing to correlate expansion results of the ASTM C1260 test to those seen in the ASTM C1293 test, exposure blocks, and field performance is required.

2.7   Acknowledgements

2.8   References

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Using Supplementary Cementitious Materials to Mitigate Alkali-Silica Reaction in Mortar Bars Made with Recycled Concrete Aggregate

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3. Second Manuscript

Using Supplementary Cementitious Materials to Mitigate Alkali-Silica Reaction in Mortar Bars Made with Recycled Concrete Aggregate

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Abstract: The use of recycled concrete aggregate (RCA) in concrete is a promising method to decrease the amount of demolished concrete sent to landfills. Replacing natural aggregate with RCA in new concrete is severely hindered, however, by a lack of technical information on the long-term durability of this concrete and a general perception of RCA as a substandard material. This research project investigated the efficacy of replacing portland cement with supplementary cementitious materials (SCMs), known to mitigate alkali-silica reaction (ASR) in concrete with virgin aggregates, to control ASR in concrete incorporating reactive RCA. The SCMs investigated as part of this study included: fly ash (class F), silica fume, and metakaolin. The results of modified alkali-silica reactivity tests, ASTM C1260 and ASTM C1567 (AMBT), are presented for two different recycled concrete aggregates when using 100% portland cement, binary blends of portland cement and fly ash, and ternary blends of portland cement, fly ash and metakaolin or silica fume. The results indicate that that SCMs can effectively mitigate ASR in concrete made with RCA. A 40% replacement of portland cement with class F fly ash reduced expansions to below 0.10% in the AMBT for concrete containing 100% recycled concrete aggregate. The ternary blend, however, of portland cement with a class F fly ash and metakaolin was most effective for both RCAs tested in this study. Higher levels of mitigation may be required for some RCAs, compared to the level required to mitigate ASR in concrete made with their original natural aggregates, depending on the age and composition of the RCA.

Keywords: Recycled concrete aggregate, alkali-silica reactivity, sustainable construction, supplementary cementitious materials, metakaolin, silica fume, fly ash

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3.1   Introduction

Incorporating recycled concrete aggregate (RCA) into new concrete is a promising way to increase the use of sustainable construction materials in the concrete industry. Only 66% of the concrete waste produced in the U.S. is recycled, with the majority of that being used as road sub-base. Only 6% of RCA is used as aggregate in new concrete [1]. The low usage rate of RCA in new concrete is partially because it is considered a sub-standard construction material [2, 3], and also because of a lack of proper technical guidance, testing standards, and specifications for using RCA as a replacement for aggregate in new concrete. An area of particular concern is how RCA that is produced from a parent concrete that is affected by alkali-silica reaction (ASR) may affect new concrete [3, 4].

Recycled concrete aggregates are a two-phase particle consisting of the original natural coarse aggregate and the adhered mortar. The adhered mortar contains cement paste, and the original natural fine aggregate [5, 6]. Research into the mechanical properties of concrete containing recycled concrete aggregate has shown that, by limiting the amount of RCA used as replacement material in a given mixture and through proper design of a concrete mixture, similar or better concrete than that which is made with natural aggregates can be produced [7-9]. RCA that is produced from parent concrete that has shown deterioration due to ASR has shown to be reactive when incorporated into new concrete [10-16]. ASR is one of the most prevalent causes of premature concrete deterioration.

ASR deterioration occurs when the ASR gel [formed due to a reaction between the alkalies (Na^+ and K^+), hydroxyl ions (OH^-), and reactive silica)] absorbs water and swells. The swelling of the gel causes tensile forces in the concrete, and if these tensile forces exceed the tensile capacity of the concrete, cracking can occur. The reactive silica is supplied by the aggregates, with the hydroxyl ions present in the pore solution of the concrete to maintain charge balance with the cations (Namely Na+ and K+). The alkalis are provided by the cement, other admixtures and can also come from external sources such as seawater or deicing/anti-icing chemicals. The RCA may also contain additional alkalis in the adhered mortar or from ASR gel already present in the RCA [14]. Cracking will allow more moisture to enter the system, which will subsequently be absorbed by the ASR gel likely resulting in further expansion and additional cracking. ASR can be mitigated through the use of

supplementary cementitious materials (SCM) such as fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, or silica fume incorporated into the fresh concrete mixture [17-21]. Though the mechanisms by which SCMs works to mitigate ASR are not fully understood, it is believed that during hydration they help to bind alkalis, either through the creation of calcium silicate hydrate (C-S-H) or the conversion of calcium hydroxide (CH) to C-S-H, making them less available for the ASR reaction [18, 22]. SCMs also help to reduce ASR by reducing the cement content, which can have a dilutional effect in reducing the amount of available alkalis in the system. The SCMs also create physical changes in the concrete by strengthening the system which increases the amount of pressure required by the ASR gel to cause cracking; and by reducing permeability of the system preventing the ingress of moisture[22].

Determining the amount of SCMs required for mitigating ASR in concrete requires testing. ASTM C1567 (AMBT) and ASTM C1293 (concrete prism test (CPT)) can be used to determine what levels of SCMs need to be incorporated to reduce expansions to acceptable levels [23, 24]. The CPT test method is generally considered the most accurate [25], however the test takes two years to complete when assessing SCMs whereas the AMBT can be completed in 16 days. It is generally recommended to run both tests concurrently. Malvar and Lenke [26] developed a chemical index to determine the amount of fly ash required to mitigate ASR in concrete made with natural aggregates. The equation was developed by examining the results of combinations of a wide range of cements, fly ashes and various reactive aggregates in the AMBT. The chemical index uses the characteristics of the particular fly ash and cement to predict how much fly ash, by weight percent replacement of cement, will be required to mitigate ASR for a particular combination of cement and aggregate. In essence this can provide a strong starting point to eliminate the need for vast quantities of testing where an optimum dosage can be predicted and then that dosage rate and rates slightly higher and slightly lower can be tested to confirm the amount of fly ash needed to control the reaction. However, it is not known if this methodology applies to concrete produced with RCA.

The amount of expansion observed due to ASR from the RCA is dependent on the amount of RCA incorporated into the mixture, the reactivity of the original natural aggregates, and

the amount of processing the RCA goes through to attain correct gradation for the requisite tests [15, 16]. It has also been determined that the ASTM C1260/C1567 accelerated mortar bar test (AMBT), is an effective way to detect alkali-silica reactivity in RCA [15, 16]. Previous work has shown, however, that SCMs are not *as effective* at mitigating ASR in concrete made with RCAs compared to concrete made with natural aggregates [15]. In other words higher dosages of the same SCMs may be needed to control ASR in concrete incorporating RCA compared to the concrete produced with original natural aggegate (the same type present in the RCA).

3.2 Research Significance

The purpose of this study was to determine the effectiveness of SCMs to mitigate ASR in concrete made with RCA. Of particular interest was determining if there were differences between stockpiled RCA with unknown parent concrete mixtures and RCA that was laboratory created. A class F fly ash, and blends of a class F fly ash and metakaolin or silica fume were studied for their effectiveness in reducing expansions due to ASR in mortar bars in the ASTM C1567 test. Also examined was the effectiveness of the Malvar and Lenke chemical index equation to predict the amount of fly ash required to mitigate ASR in concrete made with RCA. This study contributes significantly to the overall knowledge on mitigating ASR in mixtures made with RCA. It is one of the first studies to examine the efficacy of ternary blends of portland cement and SCMs, and also provides information on the applicability of standard test methods.

3.3 Experimental Investigation

3.3.1 Materials

Aggregates

Two sources of recycled concrete aggregates were obtained for this study. One was produced from the crushing of an outdoor exposure block that was cast as part of a long-term field and laboratory correlation study on ASR performed at the University of Texas at Austin, Texas, USA [27]. The exposure blocks were cast under controlled laboratory conditions and measured nominally 15.75 x 15.75 x 28 in. (40 x 40 x 70 cm). The second RCA was produced by crushing slabs that had been produced from returned concrete at an

Oregon, USA ready-mix facility. This material represented an unknown stockpiled material, which consisted of combinations of parent concretes that contained various water/cementitious materials (w/cm) ratios, as well as differing admixtures in unknown proportions, in essence providing a more realistic material that could be made available for use in concrete applications in the field. Table 3-1 summarizes the information regarding these RCAs. This table includes information on the source of the RCA and the original natural aggregate, as well as the original natural aggregate's performance in typical ASR tests.

Table 3-1: RCA mineralogy and sources

Recycled Concrete Aggregate	Natural Aggregate Mineralogy	Recycled Concrete Aggregate Origin	Source Type	Natural Aggregate Mortar Bar Expansion in ASTM C1260 Test (14 d exp. %)	Natural Aggregate Concrete Prism Expansion in ASTM C1293 Test (1-year exp %)	Abs. Capacity of Recycled Concrete Aggregate (%)
Jo-R	Mixed quartz/ chert/ feldspar sand (FA)	Exposure block from Austin, Tx	Laboratory created	0.64	0.59	9.55
Ca-R	Silicious river gravel (CA and FA)	Returned concrete stockpile at Oregon readymix facility	Stockpile	FA: 0.81 CA: 0.59	Unknown	9.32

Cementitious Materials

An ASTM C 150 type I/II high alkali (HA) cement was used for all mixtures cast in this study. A class F fly ash, ground granulated blast furnace slag (GGBFS), silica fume, and metakaolin were used as supplementary cementitious materials. Oxide analyses for all cementitious materials are listed in Table 3-2.

Table 3-2: Cementitious materials oxide analysis

Oxide	Oxide Short	Type I/II HA Cement	Fly Ash	Metakaolin	Silica Fume
Silicon Dioxide	SiO_2	19.57	54.06	51.11	> 85.0
Aluminum Oxide	Al_2O_3	4.88	16.36	45.71	-
Iron Oxide	Fe_2O_3	2.91	6.01	0.01	-
Total (SiO_2 + Al_2O_3 + Fe_2O_3)		27.36	76.42	0.29	< 1.5
Calcium Oxide	CaO	60.82	11.16	0.18	-
Magnesium Oxide	MgO	2.52	4.14	-	-
Sodium Oxide	Na_2O	0.27	3.3	-	< 3.0
Potassium Oxide	K_2O	0.97	1.86	-	-
Total Alkalies	Na_2O_{eq}	0.91	1.55	0.09	-
Sulfur Trioxide	SO_3	3.32	0.64	-	-
Loss on Ignition		2.82	0.24	-	< 6.0

3.3.2   Procedures

The test performed as a part of this study was the accelerated mortar bar test (AMBT) as described in ASTM C1567: Standard Method for Determining the Potential Alkli-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method) [23]. The ASTM C1567 test was developed based on modifications to the ASTM C1260 [28] test which is used to determine the alkali silica reactivity of aggregates [25]. The test is performed as follows:

Mortar prisms that measure 1 x 1 x 11.25 in. (25 x 25 x 285 mm) were cast at a fine aggregate to cementitious materials ratio of 2.75:1 and a w/cm of 0.47. A stainless steel gage stud was cast into both ends of each bar to provide an effective 10.00 ± 0.10 in. (254 ± 2.54 mm) gage length. After curing for 24 ± 2h in 95% or higher relative humidity and 73 ± 3°F (23 ± 2°C), the mortar bars were submerged in room temperature tap water and placed in a $176 \pm$

3.6°F (80 ± 3.6°C) oven where they equilibrated before the next reading. The initial, or zero, reading of the bars was taken 24 ± 2h later and the bars were quickly transferred to a solution of 1 N NaOH which was already at 176 ± 3.6°F (80 ± 3.6°C). The bars then remained in 1 N NaOH at 176 ± 3.6°F (80 ± 3.6°C) for a period of 28 days [28]. Several measurements were taken throughout this time period at approximately the same time each day. For this study, length measurements were taken at 0, 1, 3, 5, 7, 10, 12, 14, 17, 21, 24, and 28 days. Length change was recorded to the nearest 0.0001 in. (0.0025 mm) and results are presented for the average of three prisms to the nearest 0.01% according to ASTM C 1567.

Expansion criteria for this test fall into two categories within ASTM C1567 based on expansion measured 16 days after casting (14 days after immersion in 1 N NaOH). Expansion of less than 0.10% is generally considered to be indicative of innocuous behavior, that is the aggregate's reactivity will likely not be high enough to cause deleterious expansions in concrete in the field. Expansions of more than 0.10% indicate that the aggregates are potentially deleterious [28]. Some testing agencies and researchers monitor the specimens longer, typically to 28 days after initial submersion in the 1 N NaOH solution, with continued periodic measurements. However, research has shown that using the 0.10% expansions limit on a 28-day test does not correlate as well with field performance as a 14-day test with the same 0.10% expansion limit. Some aggregates will register as "potentially deleterious" when they actually perform satisfactorily in the field [25]. Neither test duration, 14-days or 28-days, is perfect, however the 14-day expansions have been shown to correlate better with other ASR tests and field conditions [25]. Results using the 14-day test have been shown to produce false results, particularly with granitic gneisses and metabasalts where the aggregate has shown to perform satisfactorily in the AMBT, but produced deleterious expansions in the field [28]. These non-indicative results demonstrate the importance of using multiple test methods and correlating results with field results to truly understand the reactivity of an aggregate. Expansions from mortar bars created as a part of this study are shown here up to 28 days for informational purposes (e.g. for those agencies that specify different limits). The 14-day expansion criteria at 0.10% was used to evaluate the reactivity of the RCA and combinations of SCMs evaluated in this study.

The ASTM C1567 test requires a specific gradation of aggregate to be used when casting the mortar bars used in the test [23]. To meet the gradation required for this, where all particles must be between the sizes of 0.157 and 0.0059 in. (4.75 mm to 150 μm) in diameter, the RCA must be crushed using mechanical means. Previous work has shown that material that is re-crushed to the proper gradation after being delivered from the large scale crushing facility will produce higher amounts of expansion than material that is already at the appropriate size from the large scale crushing facility [15, 16]. This is believed to be due to the increase in the amount of original natural aggregate content in the RCA that occurs through successive levels of crushing [29]. For this study, only re-crushed RCA was used.

ASTM C1567 requires that any crushed aggregate be washed and dried prior to being used in the mortar bar mixture. Previous researchers using RCA in new concrete have expressed concern that washing these aggregates may result in a reduction in expansions because available alkalis are leached away [13, 15]. Therefore, the following washing procedure was developed by Adams et al. to limit the amount of washing to prevent alkalis or calcium from being leached from the material, erosion of adhered mortar, or hydration of unhydrated cement particles [16]:

- Sieve each aggregate, and keep separated according to each fraction retained on sieve sizes;
- Measure out about 3.5 lbs (1600 g) of material onto a fine sieve;
- Wash aggregate using a rubber hose with a fanned-spray hose nozzle for the following times 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 aggregate into a 230 °F (132 °C) oven to dry for 24 ± 2 hours before using.

The absorption capacity was found according to the technique described in ASTM C128 [30], which has been found to be applicable for use with RCA [16]. The absorption capacities for these RCAs are shown in .

High early expansion rates have been seen to occur in ASR testing due to expansion of the particle as it absorbs water from the surrounding matrix, if the RCA is used in the oven dry

state [14]. To prevent this, and to aid in workability problems that can be caused by the higher absorption capacity of RCA compared to original natural aggregates [31, 32], the RCA was soaked for 30 minutes in their mixture water prior to being mixed with the other cementitious materials to cast the mortar bars. This required an alteration of the mixing procedure used in the ASTM C1567 test. The mixing procedure used was developed by Adams et al. for use in the ASTM C1260 test [16]. It is as follows:

- After washing and drying the aggregates, 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 efficacy of a binary blend of a class F fly ash and portland cement to reduce ASR induced expansions was tested first for both the Jo-R and Ca-R aggregates. The Jo-R aggregate was tested at a 100% replacement level of RCA, the Ca-R was tested at 25%, 50%, and 100% RCA replacement levels. The levels of fly ash replacement were determined using the equation determined by Malvar and Lenke, at a 90% confidence level [26].

A study was performed by Malvar and Lenke to determine the efficiency of a fly ash, and thus the replacement needed to mitigate ASR expansions. This involved analyzing the input of various chemical constituents of both fly ash and cement. From this, they were able to develop an equation that allows the user to input the chemical constituents and receive a result of the mass percent of fly ash needed to replace cement to control the reaction [26]. They divided the chemical constituents of cement and fly ash into two groups: (1) constituents that promoted ASR and (2) constituents that prevent ASR. The constituents that were classified as promoting ASR were calcium oxide (CaO), alkalis (Na_2O and K_2O, expressed as Na_2O_{eq}), magnesium oxide (MgO) and sulfur trioxide (SO_3). The constituents that worked to prevent ASR were identified as silicon dioxide (SiO_2), aluminum trioxide

(Al_2O_3), and iron oxide (Fe_2O_3). These were then expressed as calcium oxide equivalents (CaO_{eq}) and silicon dioxide equivalents (SiO_{2eq}). Weighting factors were also developed to account for the difference in reactivity between the various chemical constituents and were then applied to the calcium oxide and silicon dioxide equivalents. These were determined to be α=5.64 and β=1.14, respectively. Oxide contents were entered as percent mass of total fly ash or portland cement [26]. These equations can be seen in Equation 3-1 and Equation 3-2:

$$CaO_{eq\alpha} = CaO + \alpha(0.905Na_2O_{eq} + 0.595K_2O + 1.391MgO + 0.700SO_3)$$

Equation 3-1

$$SiO_{2eq\beta} = SiO_2 + \beta(0.589Al_2O_3 + 0.376Fe_2O_3)$$

Equation 3-2

A set of constants were also developed that changed depending on the level of reliability required by the user to determine how much fly ash would be needed to reduce ASR expansions. For a 90% reliability level that ASR would be mitigated values used by Malvar and Lenke were: a_1=0, a_2=1.0244, a_3=0.6696, and a_4=0.1778. Finally, the percent mass replacement of fly ash required to mitigate ASR using a specific combination of aggregate, cement, and fly ash was determined to be [26]:

$$W = \frac{1 - g(\frac{0.08}{E_{14c}})}{(1 - \frac{CaO_{eq\alpha\,fa}}{CaO_{eq\alpha c}}) - (1 - \frac{SiO_{2eq\beta\,fa}}{SiO_{2eq\beta c}})g(\frac{0.08}{E_{14c}})}$$

Equation 3-3

Where:

W = mass percent replacement of fly ash required to mitigate ASR
E_{14c}= Percent expansion of mortar bars in the accelerated mortar bar test at 14 days

$$g = \frac{a_4(\tanh^{-1}(\frac{2(\frac{0.08}{E_{14c}}) - (a_1 + a_2)}{a_2 - a_1})) + a_3}{\frac{0.08}{E_{14c}}}$$

$CaO_{eq\alpha fa}$= Calcium oxide equivalent, with the alpha factor applied, for the fly ash
$CaO_{eq\alpha c}$= Calcium oxide equivalent, with the alpha factor applied, for the portland cement
$SiO_{2eq\beta fa}$= Silicon dioxide equivalent, with the beta factor applied, for the fly ash

SiO$_{2eq\beta c}$= Silicon dioxide equivalent, with the beta factor applied, for the portland cement

It is important to note that this equation was developed empirically based on the evaluation of five studies using twenty-nine fly ashes and five aggregates. The chemical index equations may not be accurate for all combinations of materials and testing should always be performed prior to using the fly ash replacement level stipulated by this formula in field concrete. The equation does, however, provide a starting point for engineers to use to develop the appropriate fly ash replacement dosage to mitigate ASR. The predicted amount of the class F fly ash required to reduce expansions in mortar bars made with RCA, according to the equation developed by Malvar and Lenke are provided in Table 3-3.

Table 3-3: Fly ash mitigation requirements per Malvar and Lenke[26]

RCA	RCA Replacement Level (%)	Expansions at 14-days in ASTM C1260 (%)	Fly Ash Required to Reduce Expansions Below 0.10% at 14-day in ASTM C1567 (% weight)
Jo-R	100	0.12	17
Ca-R	100	0.51	38
Ca-R	50	0.53	35
Ca-R	25	0.29	30

Actual cementitious material replacement levels used were rounded up to the nearest 5% replacement level. Previous research has shown that when mitigating ASR in concrete containing RCA, it may take more of a particular fly ash to reduce expansions compared to that needed to reduce expansions for natural aggregate concrete made with the same original natural aggregate as in the RCA [15]. Specimens were also cast using 10% to 20% more fly ash than that recommended by Malvar and Lenke for upper bounds to verify the effectiveness of the predictive equations.

The efficacy of ternary blends was also examined as part of this study. Ternary blends using class F fly ash, silica fume and portland cement, and class F fly ash, metkaolin and portland cement were incorporated into the mortar bar mixtures. These blends were also investigated with the same Jo-R and Ca-R aggregates; with the Jo-R aggregate tested at a 100%

replacement level of RCA, and the Ca-R tested at 25%, 50%, and 100% RCA replacement levels. The full testing matrix can be seen in Table 3-4.

Table 3-4: Cementitious material content by mixture

Mixture Name	RCA Used	Replacement Level of RCA (%)	Portland Cement Content (% of Cementitious Materials)	Class F Fly Ash Content (% of Cementitious Materials)	Silica Fume Content (% of Cementitious Materials)	Metakaolin Content (% of Cementitious Materials)
Jo-R-100	Jo-R	100	100	-	-	-
Jo-R-100-20FA	Jo-R	100	80	20	-	-
Jo-R-100-30FA	Jo-R	100	70	30	-	-
Jo-R-100-40FA	Jo-R	100	60	40	-	-
Jo-R-100-25FA_10MK	Jo-R	100	65	25	-	10
Jo-R-100-25FA_5SF	Jo-R	100	70	25	5	-
Ca-R-100	Ca-R	100	100	-	-	-
Ca-R-100-40FA	Ca-R	100	60	40	-	-
Ca-R-100-50FA	Ca-R	100	50	50	-	-
Ca-R-100-25FA_10MK	Ca-R	100	65	25	-	10
Ca-R-100-25FA_5SF	Ca-R	100	70	25	5	-
Ca-R-50	Ca-R	100	100	-	-	-
Ca-R-50-35FA	Ca-R	50	65	35	-	-
Ca-R-50-45FA	Ca-R	50	55	45	-	-
Ca-R-50-25FA_10MK	Ca-R	50	65	25	-	10
Ca-R-25	Ca-R	100	100	-	-	-
Ca-R-25-30FA	Ca-R	25	70	30	-	-
Ca-R-25-40FA	Ca-R	25	60	40	-	-
Ca-R-25-25FA_10MK	Ca-R	25	65	25	-	10
Ca-R-25-25FA_5SF	Ca-R	25	70	25	5	-

3.4 Results

The results of the mitigation techniques used on the Jo-R RCA can be seen in Figure 3-1 and Figure 3-2.
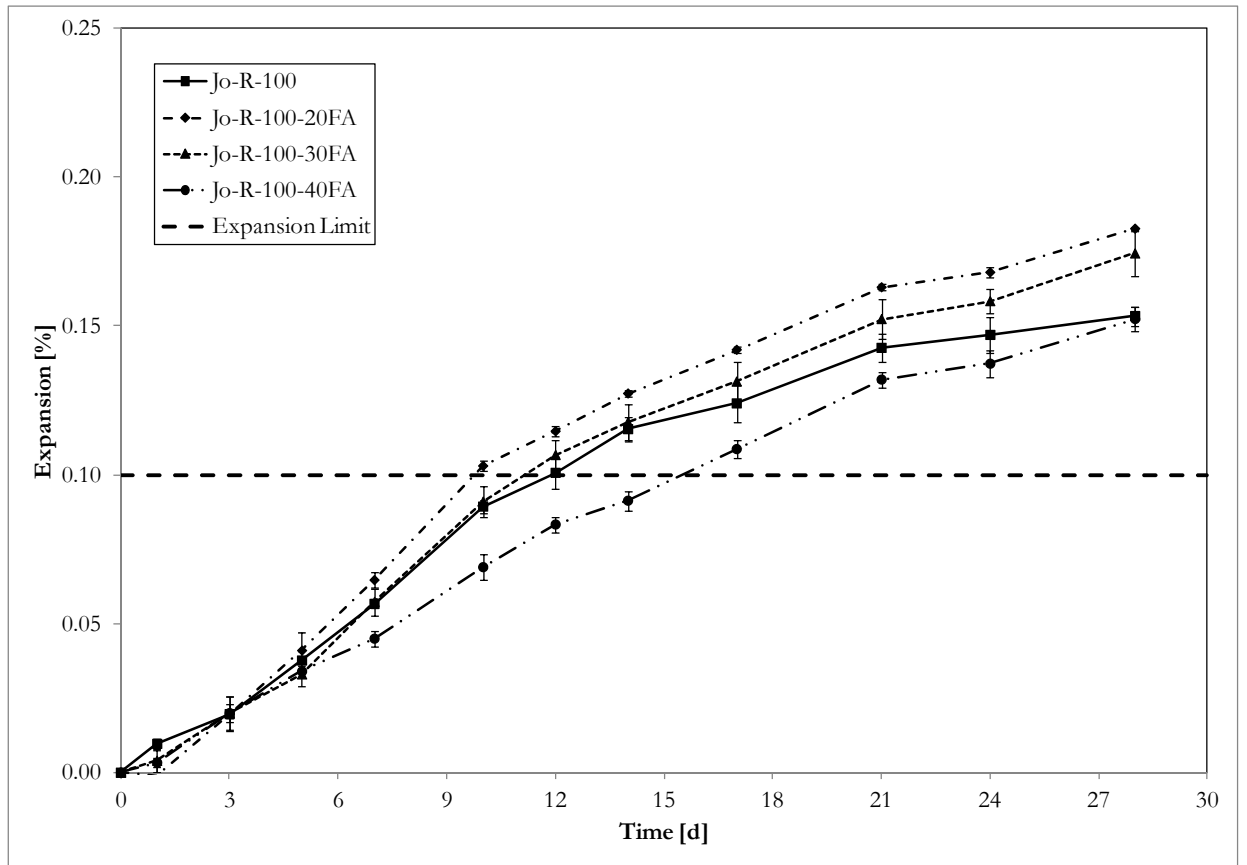
Figure 3-1: Expansion as a function of time for Jo-R RCA and various replacement levels of class F fly ash
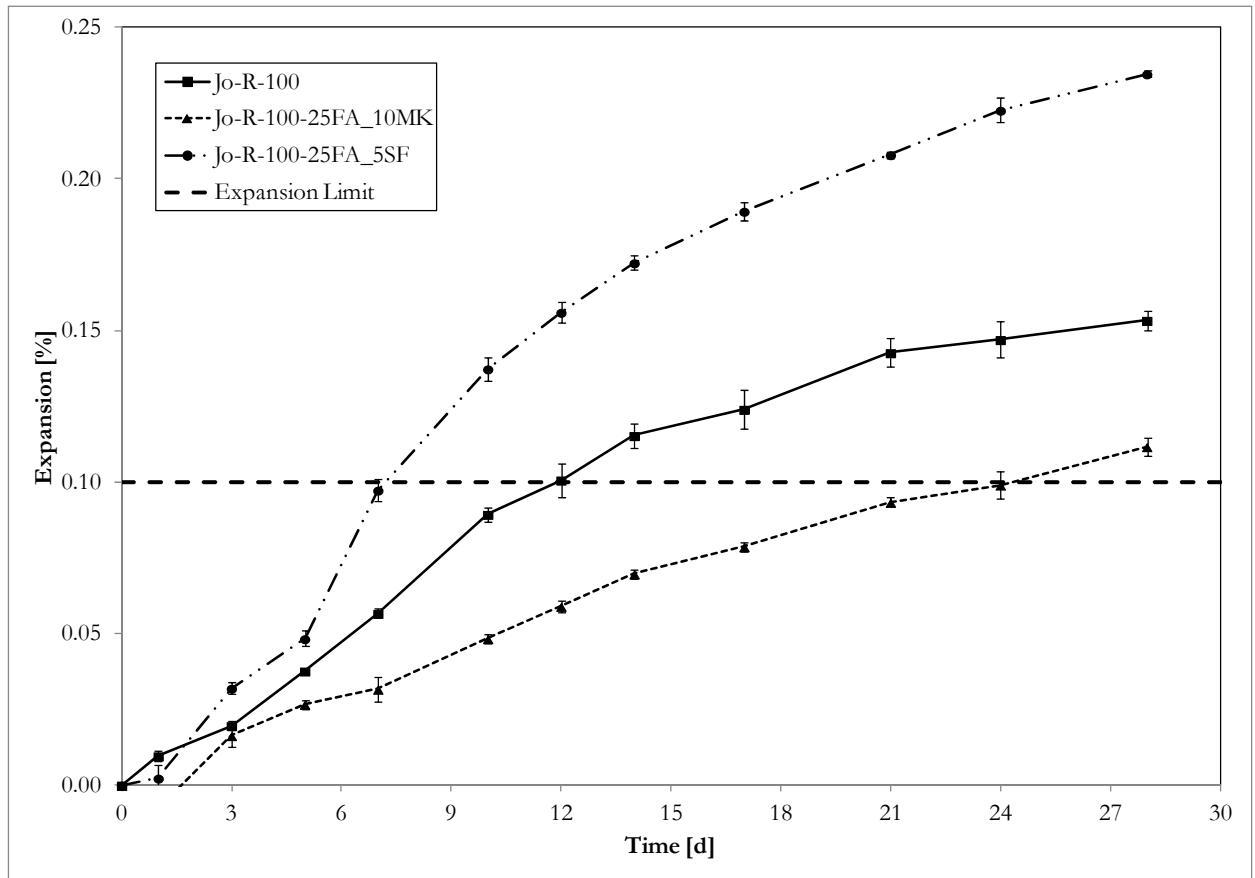
Figure 3-2: Expansions as a function of time for Jo-R and ternary blends of portland cement, class F fly ash, and metakaolin or silica fume

At the fly ash replacement level suggested by the chemical index equation developed by Malvar and Lenke, 20% for Jo-R-100, expansions due to ASR actually increase. The 30% fly ash replacement level reaches the same expansion as the control at day 14. A 40% fly ash replacement in the Jo-R mixture resulted in a decrease in expansion; the 40% fly ash replacement reduced expansions to be below the 0.10% expansion limit that indicates the mixture will likely not cause deleterious expansions in concrete. The ternary blend with portland cement, fly ash, and metakaolin 14-day expansions of the mortar bars made with Jo-R to below the 0.10% expansion limit. Table 3-5 shows the 14-day expansions and their standard deviations and coefficients of variation for these results.

Table 3-5: 14-day expansions, standard deviations, and coefficients of variation for Jo-R mixtures

Mixture	14-day Expansion (%)	Standard Deviation in 14-day Measurement	Coefficient of Variation
Jo-R-100	0.12	0.004	3.50%
Jo-R-100-40FA	0.09	0.003	3.52%
Jo-R-100-30FA	0.12	0.006	5.12%
Jo-R-100-20FA	0.13	0.001	0.91%
Jo-R-100-25FA_10MK	0.07	0.002	2.19%
Jo-R-100-25FA_5SF	0.17	0.002	1.34%

The coefficient of variation limit in the ASTM C1567 is 2.94%. The Jo-R-100, Jo-R-100-40FA, and Jo-R-100-30FA specimens exceed this prescribed coefficient of variation limit. The other Jo-R mixture results are within the coefficient of variation limits.

The expansion of the Ca-R mortar bars with 100% RCA replacement and various mitigation techniques is shown in Table 3-7.
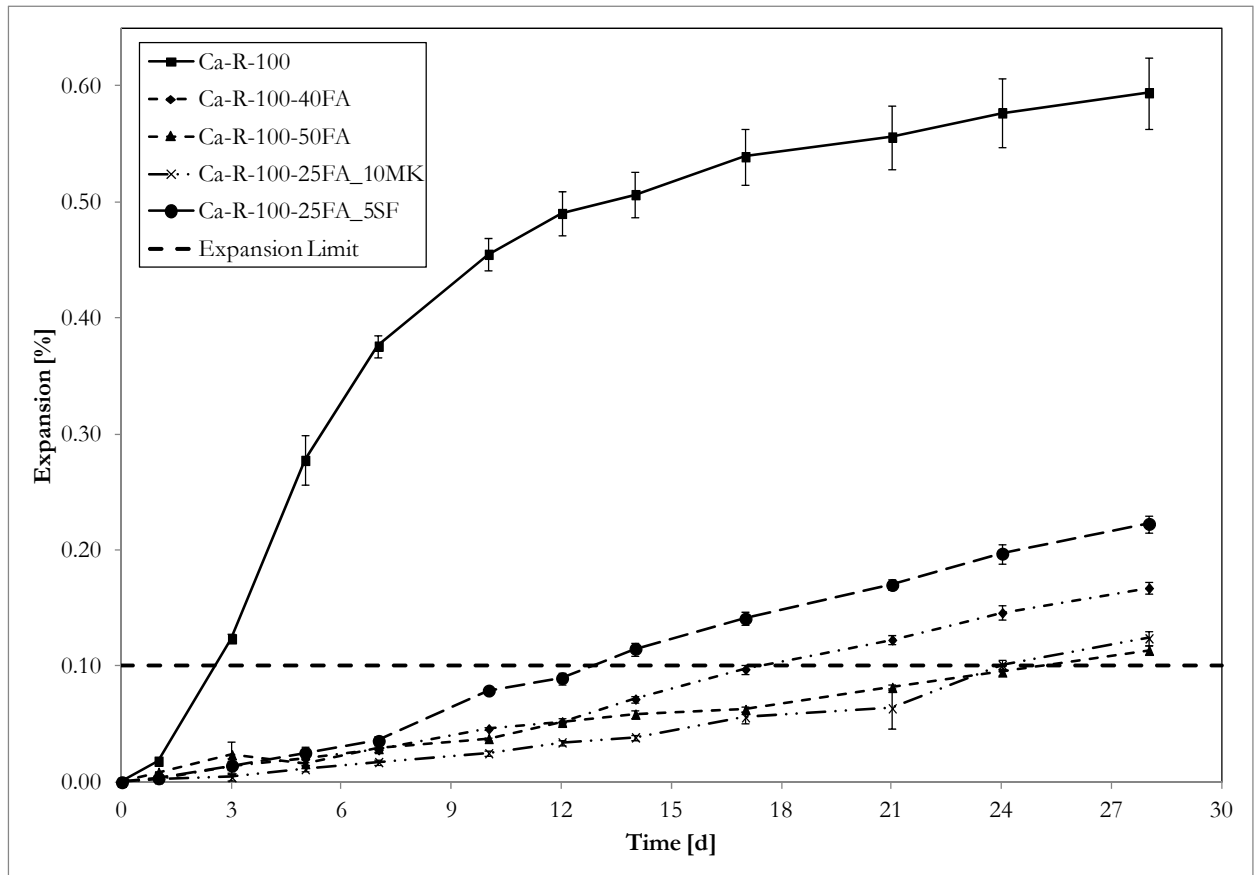
Figure 3-3: Expansions as a function of time for Ca-R with various cementitious material blends

All mitigation techniques except for the ternary blend with portland cement, silica fume, and fly ash, were able to decrease the expansion of the mortar bars to below the 0.10% expansion limit at 14-days. The ternary blend containing silica fume, Ca-R-100-25FA_5SF did significantly decrease expansion compared to the mortar bars made with just portland cement (e.g. the control), Ca-R-100; though the expansion was still above the 0.10% limit at 14 days. The ternary blend containing metakaolin, Ca-R-100-25FA_10MK was able to reduce the ASR induced expansions at 14-days by the most signficant amount. Table 3-6 shows the 14-day expansions and their standard deviations and coefficients of variation for the mortars containing Ca-R.

Table 3-6: 14-day expansions, standard deviations and coefficients of variation for Ca-R-100, Ca-R-50, and Ca-R-25 mixtures

Mixture	14-day Expansion (%)	Standard Deviation in 14-day Measurement	Coefficient of Variation
Ca-R-100	0.51	0.020	3.95%
Ca-R-100-40FA	0.07	0.003	4.26%
Ca-R-100-50SL	0.06	0.003	5.21%
Ca-R-100-25FA_10MK	0.04	0.003	6.51%
Ca-R-100-25FA_5SF	0.12	0.006	4.84%
Ca-R-50	0.43	0.010	2.42%
Ca-R-50-35FA	0.09	0.002	2.30%
Ca-R-50-45FA	0.05	0.001	1.89%
Ca-R-50-25FA_10MK	0.04	0.004	9.94%
Ca-R-25	0.29	0.013	4.63%
Ca-R-25-30FA	0.10	0.001	1.17%
Ca-R-25-40FA	0.06	0.001	2.05%
Ca-R-25-25FA_MK	0.03	0.009	26.70%
Ca-R-25-25FA_5SF	0.09	0.002	1.77%

For this set of data, the Ca-R-100 sample sets , as well as the Ca-R-25, Ca-R-25FA-40MK sets exceeded the coefficient of variation limits stated for within-laboratory precision in ASTM C1567, 2.94%. For the Ca-R-50 at various SCM replacement levels, all sets were within the acceptable coefficient of variation for within-laboratory precision in ASTM C1567.

The Malvar and Lenke equations predicted that to reduce the expansions of the Ca-R's original natural coarse aggregate below the 0.10% expansion limit would require a 40% replacement of the fly ash used in this study. Testing showed that the 40% replacement of fly ash in the mortar bars containing the Ca-R's original natural coarse aggregate reduced expansions from 0.59% to 0.07%. The Malvar and Lenke equations predicted that reducing the Ca-R mortar bar's expansions to below 0.10% would require a 40% replacement as well. This prediction also proved to be a strong estimate, with a 40% fly ash replacement reducing expansions from 0.51% to 0.07% in the Ca-R 100% RCA replacement level mortar bars.

A summary of 14-day and 28-day expansions for all mortar bar sets can be seen in Table 3-7.

<div align="center">**Table 3-7: Summary of expansions**</div>

Mixture Name	14-day expansions (%)	28-day expansions (%)
Jo-R-100	0.12	0.15
Jo-R-100-20FA	0.13	0.18
Jo-R-100-30FA	0.12	0.17
Jo-R-100-40FA	0.09	0.15
Jo-R-100-25FA_10MK	0.07	0.11
Jo-R-100-25FA_5SF	0.17	0.23
Ca-R-100	0.51	0.59
Ca-R-100-40FA	0.07	0.17
Ca-R-100-50FA	0.06	0.11
Ca-R-100-25FA_10MK	0.04	0.12
Ca-R-100-25FA_5SF	0.12	0.22
Ca-R-50	0.43	0.51
Ca-R-50-35FA	0.09	0.18
Ca-R-50-45FA	0.05	0.12
Ca-R-50-25FA_10MK	0.04	0.12
Ca-R-25	0.29	0.35
Ca-R-25-30FA	0.1	0.17
Ca-R-25-40FA	0.06	0.13
Ca-R-25-25FA_10MK	0.03	0.07
Ca-R-25-25FA_5SF	0.09	0.17

In all aggregates at all replacement levels it can be seen that the blends containing metakaolin reduced 14-day expansions the most compared to all other SCM blends used. The blends using the silica fume typically performed the worst, though at lower replacement levels of RCA (50% and 25%), they were able to reduce expansions below the 14-day expansion limit of 0.10%.

3.5 Discussion

The results show that SCMs can reduce expansions in concrete made with RCA. Fly ash replacement levels at 40% were able to reduce expansions to within acceptable levels for a 100% replacement level of both the Ca-R and Jo-R aggregates. Ternary blends containing

25% class F fly ash, 10% metakaolin and 65% portland cement exhibited the best performance in reducing the expansions seen in the ASTM C1567 test when using RCA for all aggregates and RCA replacement levels. The results also show that the chemical index equation developed by Malvar and Lenke was unable to properly predict the amount of fly ash required to reduce expansions in the mortar bars created using the Jo-R aggregate; and in fact, the calculated fly ash replacement level actually caused an increase in expansion. A 20% increase over the calculated amount of fly ash replacement to reduce expansions calculated through the chemical index equation was required to reduce expansions to below 0.10% in the ASTM C1567 test using the Jo-R aggregates. However, the fly ash replacement level calculated using the equation did reduce the expansions in the mortar bars made with the Ca-R aggregate. These results are conflicting, and show that the chemical index equation may be capable predicting the required amount of fly ash to reduce expansions for some RCA and fly ash combinations, though not for all. Further research needs to be conducted to see

For both the Jo-R and Ca-R RCAs, the ternary blends containing metakaolin resulted in the most significant decrease in expansions compared to the mixtures with no SCMs. The Jo-R-100 expansion was reduced by 0.05% and the Ca-R-100, Ca-R-50, and Ca-R-25 expansions were reduced by 0.47%, 0.39%, and 0.26% respectively. The ability of metakaolin to work effectively in a ternary blend has been attributed to its small particle size, and chemical composition. During hydration, the pozzolan effectively binds alkalis without adding more reactive constituents to the system [33]. Metakaolin has a high aluminum oxide content (typically around 45%) [34]. The introduction of alumina causes the C-S-H structure to form C-A-S-H (calcium alumino silicate hydrate) which has an even greater capacity to bind alkalis than C-S-H [18, 35] (which is formed during cement hydration, and is a product of the pozzolonic reaction produced using fly ash [18]), thus further reducing alkali-silica reactivity. The silica fume ternary blend was less effective than the other SCM combinations used to reduce expansions in the mortar bars made with the Ca-R aggregate, though a reduction in expansion was observed. It has been shown that higher levels of silica fume additions may decrease expansions further, to acceptable levels [18], however higher dosages of silica fume can have negative impacts on the workability of concrete. This is a particularly acute concern when using RCA, which, due to its high absorption capacity, already decreases

workability in concrete mixtures, therefore higher replacement levels of silica fume would not be recommended.

It was observed that as the replacement level of RCA decreases (from 100%, to 50%, to 25%) the amount of fly ash required to mitigate the ASR induced expansions also decreases. The trend is also seen in the ternary blends, with the same ternary blend exhibiting more significant decreases in expansion at lower RCA replacement levels. This is likely due to the decrease in reactive material in the system, and thus a decrease in overall reactivity in the mortar bars. Current codes for structural concrete limit the amount of fly ash in a mixture to 25%, and the overall amount of SCMs in a ternary blend containing fly ash or other pozzolans and silica fume to 50% [36]. Therefore, effective ways to limit the amount of SCMs needed to control expansions can be to limit the amount of RCA used in a mixture, or carefully evaluating ternary blends. However, it is recommended that all replacement levels and SCM combinations be tested prior to being used in the field, as higher expansions have been noted at lower RCA replacement levels [16].

The results of the Ca-R aggregate's mitigation contradict previous results that have said that higher levels of mitigation are required to reduce expansions in mortar bars made with RCA, compared to those made with natural aggregates [13, 15]. The Ca-R original natural aggregates were a reactive silicious river gravel and reactive silicious river sand. These natural aggregates produced expansions of 0.59% and 0.81% for the coarse and fine natural aggregates, respectively, in the ASTM C1260 test. ASTM C1567 testing with this natural aggregate showed that a 40% fly ash replacement was able to reduce expansions to acceptable levels (0.07%) in mortar bars created with the coarse natural aggregate and 45% fly ash replacement was able to reduce expansions to acceptable levels (0.04%) in mortar bars containing the fine natural aggregate. A 40% fly ash replacement level was able to reduce the expansions to within acceptable limits (0.07%) in mortar bars created with the RCA. This may be due to the make-up of the RCA, however.

During visual examination of the Ca-R RCA it was noted that there was (visually) a relatively small amount of adhered mortar on the particles, particularly when compared to the Jo-R RCA. This indicates that the ability of SCMs to mitigate ASR in aggregates may depend on the ratio of adhered mortar to original natural coarse aggregate. However, the quantity of

adhered mortar was not quantified as a part of this study. A method to determine the adhered mortar content of an RCA was developed by Abbas et al., however this method is only applicable for use with aggregates greater in size than 0.187 in (4.75 mm) [37]. This method involves removing the adhered mortar by placing the aggregate in a sodium sulfate solution and then subjecting the submerged aggregate to five freeze/thaw cycles. The aggregate is then washed over a sieve, and the adhered mortar, which was broken down during the freeze/thaw cycling, is washed away [37]. The gradation of aggregate required for use in the ASTM C1567 test may be too small for this test method to work. Previous work has shown that amount of crushing performed on an RCA can affect its reactivity [15, 16]. This was attributed to the amount of adhered mortar on the aggregate [15, 16], which is reduced as the level of crushing is increased [29]. These past results show that the amount of adhered mortar can affect the level of reactivity in an aggregate, and subsequently may affect the efficacy of an SCM to mitigate ASR. Further testing needs to be completed to understand how the amount of adhered mortar affects the ability of SCMs to mitigate ASR in mortar bars made with RCA.

The effectiveness of the SCMs to mitigate ASR for the mixtures with the Jo-R aggregate can be seen to be less than that for the Ca-R aggregates. Comparison of the ASTM C1567 tests shows that the same mitigation techniques (40% fly ash replacement, or 25% fly ash with 10% metakolin replacement, or 25% fly ash with 5% silica fume replacement) had less of an effect of reducing expansion for the mortar bars created with the Jo-R RCA than on mortar bars created with the Ca-R RCA. This may be due to two different factors: the physical characteristics of the RCA and the age of the RCA or the level of reaction in the original natural aggregate. The RCA is a two-phase system. The Jo-R's reactive constituent was a fine aggregate that, in the RCA, is contained in the adhered mortar. The Ca-R consisted of a reactive fine and coarse aggregate, and, through visual examination, was observed to contain less adhered mortar than the Jo-R RCA. The reactive component of the RCA for the Jo-R particle is the original natural fine aggregate embedded in the adhered mortar. The SCMs, therefore, may not have as much free access to the matrix surrounding Jo-R aggregate to prevent ASR from occurring. The age of the RCA's parent concrete may also have had an impact on the ability of SCMs to mitigate expansion. The Jo-R was produced from an expansion block that was six years old, whereas the Ca-R was produced from returned

concrete at a ready mix facility, and is relatively young. This could have affected the SCM's effectiveness because the over-all reactivity was less due to the original natural aggregate having had the ability to react significantly prior to being recycled into an RCA.

An examination of the within-laboratory coefficients of variations shows that the ASTM C1567 coefficient of variation limit of 2.94% may need to be relaxed when when using RCA. 11 of the 20 different mixtures' coefficients of variation exceeded the limit of 2.94% stated in the ASTM C1567 test. Previous work by Adams et al. showed that in AMBT tests performed with RCA the multi-laboratory coefficients of variation also exceeded the limit stated [16], which is 15.2% for multi-laboratory studies [28]. However, these tests were done without including SCMs, ASTM C1260. The greater variation in test results when using RCA may be due to the inherent inconsistency in RCA particles. Different mortar bars may contain particles that have more or less adhered mortar, or reactive components of the RCA. This will affect the amount of reactivity in the mortar bars, and thus lead to more variation in testing.

3.6   Conclusion

This study demonstrated that ASR in concrete made with RCA can be effectively reduced using SCMs. Ternary blends containing portland cement, a class F fly ash, and metakaolin were the most effective in reducing expansions for both RCAs used as a part of this study. The amount of a particular SCM replacement needed for in a mixture to reduce expansions to acceptable amounts depends on several factors. These include:

- Replacement level of RCA;

- Whether the coarse or the fine original natural aggregate was the reactive component in the RCA; and

- The age of the RCA.

The amount of adhered mortar in a particular RCA may also play an important role It is recommended that testing be completed prior to the incorporation of RCA into new concrete to determine whether it is reactive, and also to determine what level of RCA

replacement, and SCM replacement is required to keep expansions within acceptable limits. This testing should include not only ASTM C1567 testing, but also ASTM C1293 (concrete prism test) testing, exposure block testing, and correlation with field results, if possible. The correlation of all these test methods is important because the two tests, ASTM C1567 and C1293, can sometimes produce conflicting results [25, 38, 39]. The ASTM C1260 test is preferred by many agencies because it can be completed in 16 days, whereas the ASTM C1293 test requires a two-year long testing program.

This study is one of the first studies to use the ASTM C1567 test to evaluate SCMs, and only the second to study the effect of ternary blends, in reducing expansions in mortar made with RCA. The information presented within this study confirms that SCMs can be used mitigate ASR caused by RCA. These findings present a significant increase in knowledge on how to mitigate ASR in concrete made with RCA. However, further research is required to determine the mechanism by which the SCMs mitigate ASR in concrete containing RCA. The effect of the two-phase RCA particle on reactivity is not yet understood. Also, further testing needs to be completed to see if current expansion limits listed in the ASTM C1567 test correlate well with the concrete prism test, exposure blocks, and field performance. It has been shown, however, that SCMs do have the potential to reduce ASR induced expansions in new concrete made with recycled concrete aggregates based on the testing presented herein.

3.7 Acknowledgements

3.8   References

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4. General Conclusion

Recycled concrete aggregate (RCA) exhibits great promise as a sustainable material that can replace natural aggregates in concrete, thereby reducing the environmental impact of the construction material. Current use is limited, however, by a lack of technical guidance and a public perception of being substandard. These can only be overcome through further research into the material which will provide better guidance on assessing and using it. This research needs to show how to classify and test the RCA, as well as how to properly incorporate it into concrete mixtures. Of particular concern to many design engineers, researchers, public agencies, and contractors is whether RCA will cause deleterious expansions as a result of alkali-silica reaction (ASR). ASR is one of the most pervasive concrete deterioration mechanisms worldwide. Currently, testing standards concerning ASR are not approved for use with RCA due to a lack of sufficient research detailing how the material reacts when subjected to the test methods.

The research presented herein has significantly added to the available information on the alkali-silica reactivity of RCA, particularly concerning test methods and mitigation techniques. Two manuscripts have been developed from this original research and were included in this thesis. The goal of this was two-fold. The first goal was to assess the applicability of the ASTM C1260 test for use as a tool to assess the reactivity of RCA. As a part of this testing, the effect of processing procedures on the reactivity of RCA was also studied. This information was included in the first manuscript: *Applicability of the ASTM C1260 Accelerated Mortar Bar Test for Alkali-Silica Reactivity Testing of Recycled Concrete Aggregates.* The manuscript presented the results of a four-laboratory multi-laboratory study. This study determined that the ASTM C1260 could be an applicable test method for use with RCA. The current precision boundaries set in the test were adequate for use when testing with the RCA, but the limit for the coefficient of variation, 15.2% for multi-laboratory studies, may need to be changed when using RCA. It was determined, however, that crushing procedures could affect the reactivity of RCA. As an aggregate is consecutively crushed to create smaller and smaller particles, the reactivity of the RCA increased. This was attributed to an increase in the available reactive material, because the adhered mortar was removed through subsequent crushing procedures.

The second goal of this study was to determine the effectiveness of supplementary cementitious materials (SCMs) in mitigating ASR for concrete containing reactive RCA. This study was performed using the ASTM C1567 testing standard. This information was included in the second manuscript: *Using Supplementary Cementitious Materials to Mitigate Alkali-Silica Reaction in Mortar Bars Made with Recycled Concrete Aggregate.* The results of this study found that SCMs could be used to mitigate ASR in concrete containing RCA. It was found that ternary blends, particularly those containing metakaolin, were much more effective in preventing ASR in the mixtures tested. There were several factors, however, that seemed to affect the efficiency of SCMs to reduce ASR expansions. These included the age of the RCA, the amount of RCA used in the mixture, and whether the RCA was made with fine or coarse original natural aggregates.

The information included in this thesis significantly advances the knowledge base on using RCA as a replacement for natural aggregates in concrete, particularly concerning the susceptibility of the material to deterioration caused by ASR. This work, however, does not provide all the information necessary to be able to safely classify and use RCA as a replacement for natural aggregate in concrete. This work is part of only a small body of work that has studied ASR with RCA; and because of this, it is important that further work be performed to confirm the results of this study. Furthermore, additional research needs to be completed to understand the mechanisms for how ASR occurs in concrete made with RCA; and if the mitigation mechanisms that occur in concrete made with SCMs and natural aggregates are the same in concrete made with SCMs and RCA. Additionally, testing needs to be completed to correlate the results presented using results from the ASTM C1293 test, exposure blocks, and field specimens. This is important because without these correlations, it cannot be known whether the expansion limits provided in the ASTM C1260 and ASTM C1567 tests are applicable to concrete made with RCA. There is still much study that needs to be performed on the alkali-silica reactivity of RCA, but this study was able to present a significant amount of new information that has indicated that RCA may be able to be used safely in new concrete, provided sufficient mitigation and aggregate classification is performed.

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Appendix A

A. Appendix A

This appendix presents additional testing data that contributed to the results in manuscript 1, but was not directly included in the manuscript.
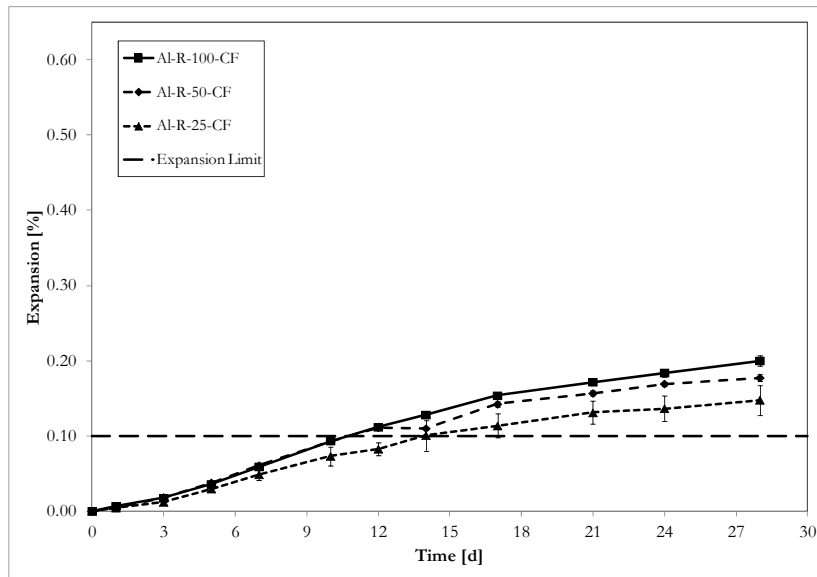

Figure A-1: Expansion as a function of time for various replacement levels of Al-R crusher's fines (Oregon State University Laboratory specimens only)
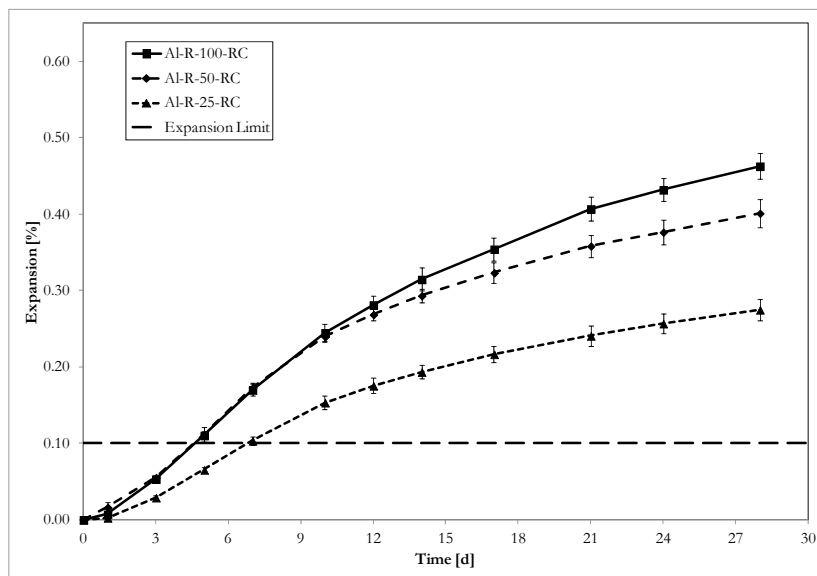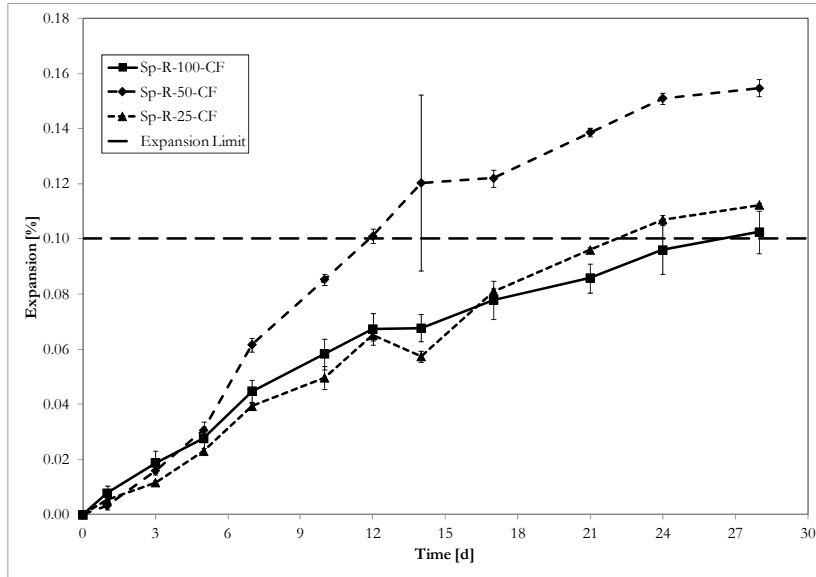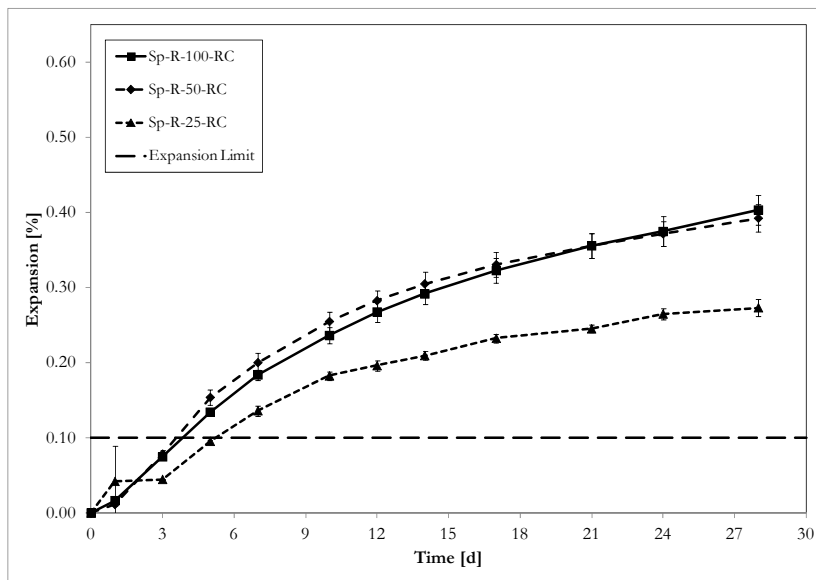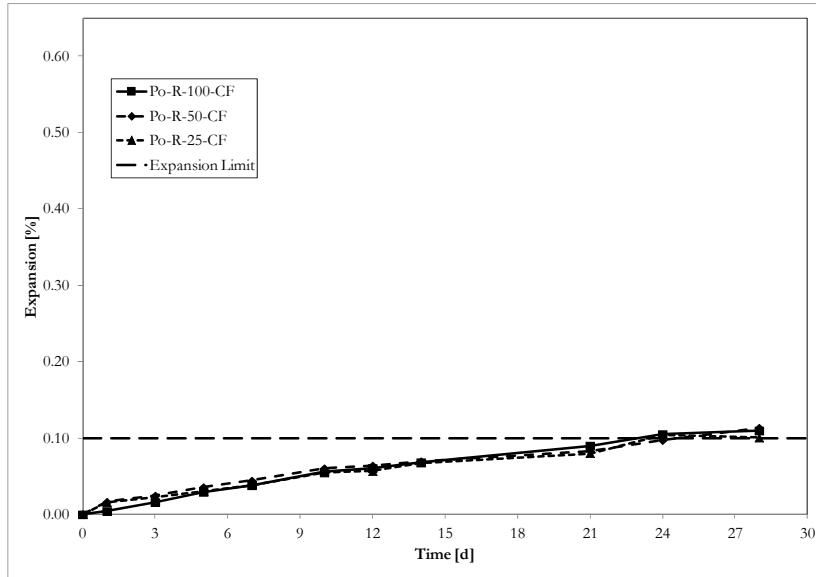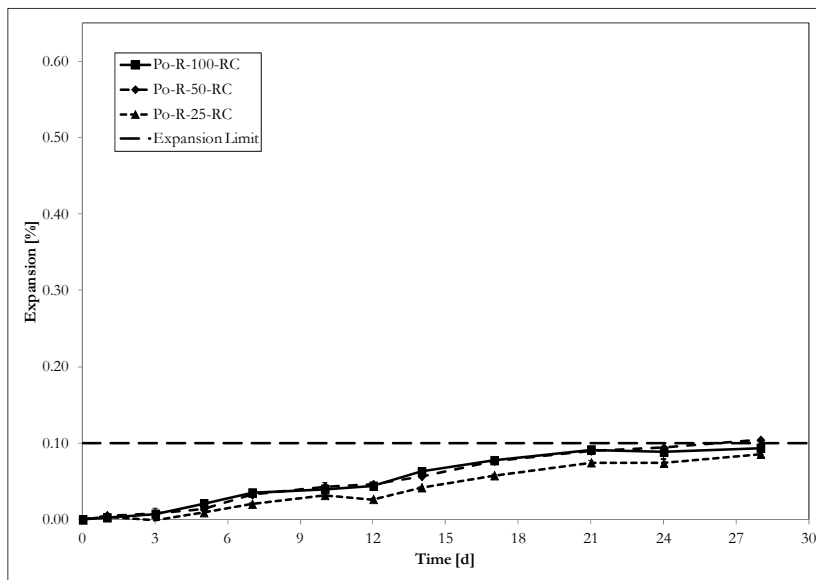

Figure A-2: Expansions as a function of time for various replacement levels for Al-R re-crushed (Oregon State University Laboratory specimens only)
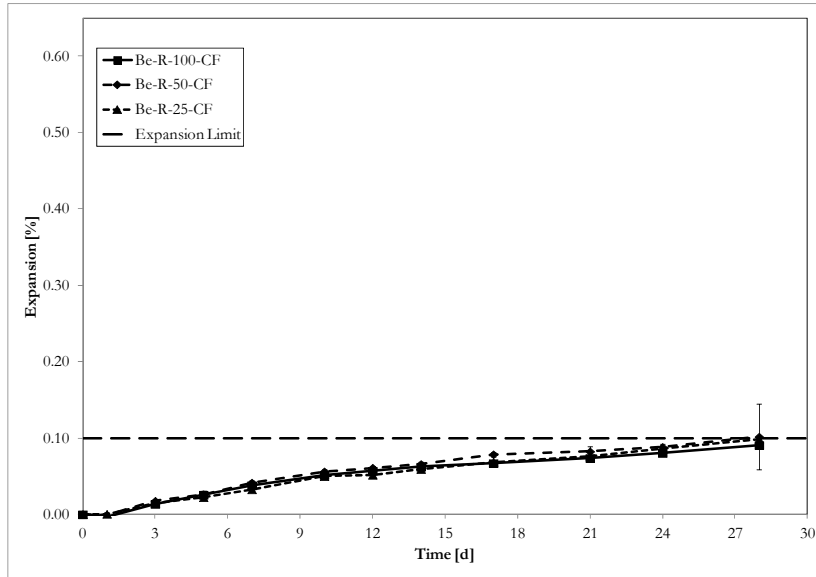
Figure A-3: Expansions as a function of time for various replacement levels for Sp-R crusher's fines (Oregon State University Laboratory specimens only)

Figure A-4: Expansions as a function of time for various replacement levels for Sp-R re-crushed (Oregon State University Laboratory specimens only)

Figure A-5: Expansions as a function of time for various replacement levels for Po-R crusher's fines (Oregon State University Laboratory specimens only)
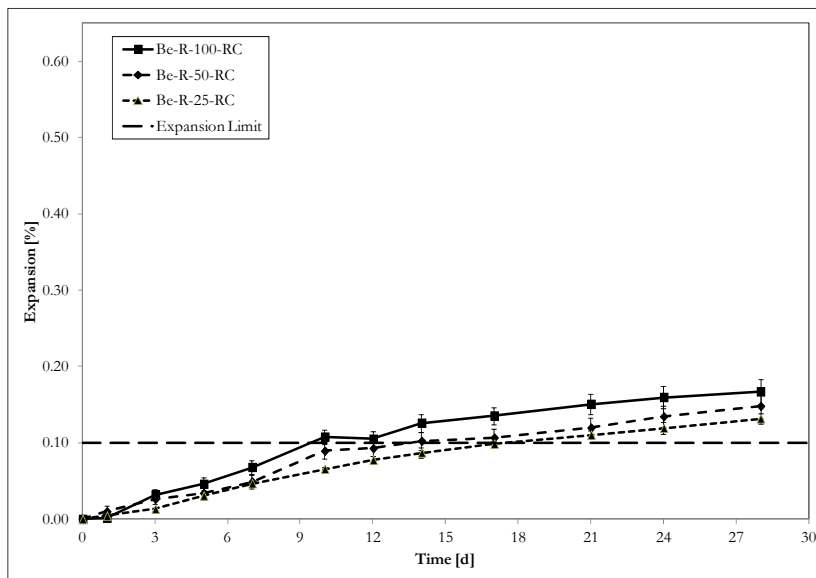

Figure A-6: Expansions as a function of time for various replacement levels for Po-R re-crushed (Oregon State University Laboratory specimens only)

Figure A-7: Expansions as a function of time for various replacement levels for Be-R crusher's fines (Oregon State University Laboratory specimens only)

Figure A-8: Expansions as a function of time for various replacement levels for Be-R re-crushed (Oregon State University Laboratory specimens only)
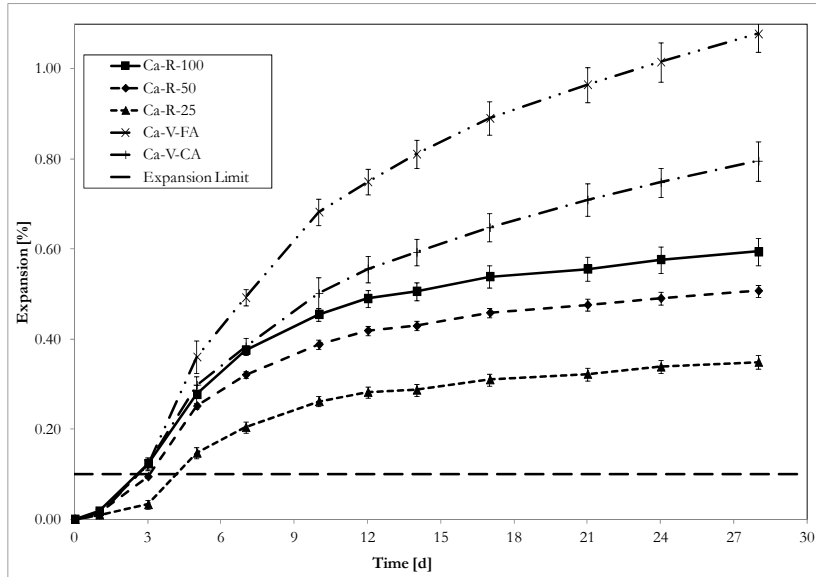
Figure A-9: Expansions as a function of time for various replacement levels for Ca-R and Ca-V (Oregon State University Laboratory specimens only)
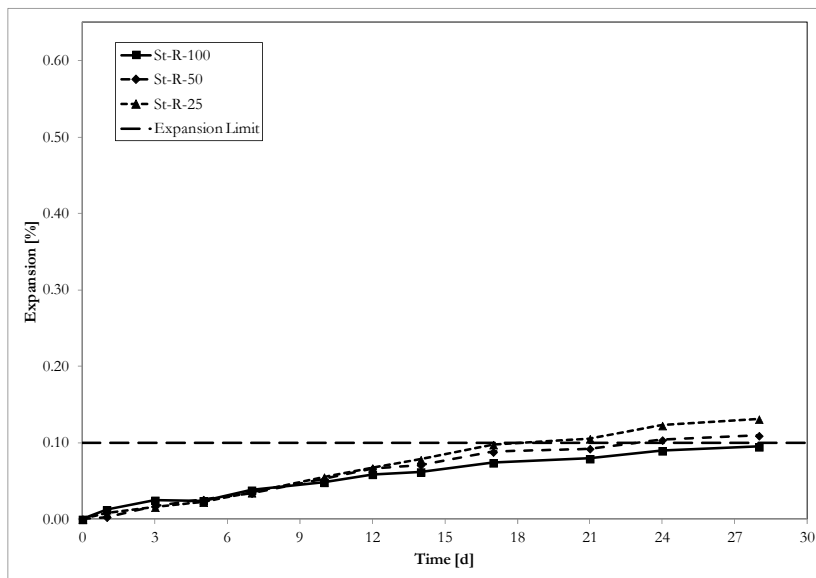

Figure A-10: Expansions as a function of time for various replacement levels for St-R (Oregon State University Laboratory specimens only)
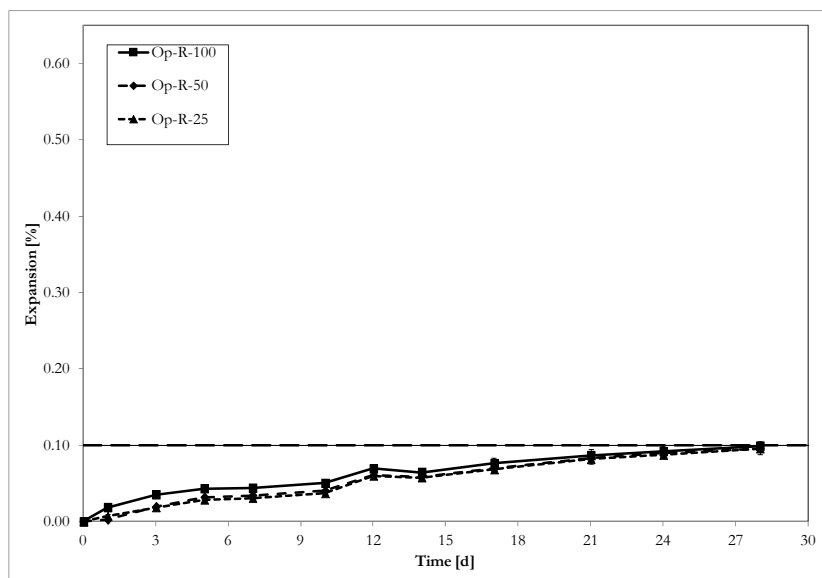
Figure A-11: Expansions as a function of time for various replacement levels for Op-R (Oregon State University Laboratory specimens only)