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Using an Ultra-accelerated Test Method to Evaluate Aggregate and Cement Combinations to Use Recycled Concrete Aggregate in New Concrete Construction



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16. Abstract The Rocky Mountain Region has experienced considerable difficulty due to the presence of alkali-silica reaction (ASR) in concrete construction. Several sources of aggregate that have produced poorly performing concrete have been removed from service. As an example, DIA runways were damaged by ASR and the repair cost exceeded 30 million. On a positive note, Wyoming Department of Transportation (WYDOT) was successful in using RCA on Interstate 1-80 and with limited ASR damage. In this portion of the road, WYDOT observed a 30 year service life. This performance, coupled with data from a previous study help confirm that using RCA combined with natural aggregates produces durable long-term concrete that will benefit the transportation network in this region. This study intends to provide experimental data that permits RCA to be used in applications beyond base fill for roads.					
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**Using an Ultra-accelerated Test Method to Evaluate
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Recycled Concrete Aggregate in New Concrete Construction**

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- Wyoming Department of Transportation

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ABSTRACT

The Rocky Mountain Region has experienced considerable difficulty because of alkali-silica reaction (ASR) in concrete construction. Wyoming Department of Transportation (WYDOT) was successful in using recycled concrete aggregate (RCA) on Interstate I-80 with limited ASR damage. Reusing concrete from demolition work has potential to produce durable concrete. A major concern with using RCA as a sustainable building material is its ASR potential, in particular if ASR damaged concrete will be recycled. In addition, a full service record is not always available for RCA. Hence, effective use of RCA requires the ability to classify whether it is reactive in terms of ASR. This study presents experimental data that permits RCA to be used in applications beyond base fill for roads. Furthermore, repeatability and reproducibility of test method was evaluated for an autoclave test. Within-laboratory precision from replicate experiments was evaluated for RCA concrete prism tests (CPT) with independent casting by three operators on different days. Inter-laboratory precision was evaluated with the participating of five external laboratories. Consistency statistics were performed in this project to analyze and identify any outlier data points. Additionally, these statistics confirmed that using RCA in CPTs did not result in additional variation compared to natural aggregates.

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1. INTRODUCTION

1.1 Background

Concrete is the most widely used construction material in the world. Reasons for the popularity of concrete include durability, low relative cost, low maintenance and high fire resistance. Despite this, exposure to aggressive environmental conditions for an extended period of time can cause premature deterioration of concrete. The lifespan of concrete can be reduced by various factors, such as reinforcement corrosion, alkali-silica reaction (ASR), chloride or sulfate attack, carbonation and leaching. Among all the concrete damage mechanisms, ASR can lead to severe durability related issues that could cause extensive damage to concrete structures. Repair works of structures affected by ASR can be very complicated, expensive and time-consuming. As early as 1940, Stanton pointed out that concrete can suffer deleterious expansion due to the use of reactive aggregates. He later confirmed to effectiveness of using pozzolans as partial replacement of cement to mitigate ASR (Stanton, 1950). Since then, researchers reported ASR expansion in concrete structures in different parts of the world (Saha et al., 2018). In 1980, Cole investigated dams in Australia suffering from deleterious cracking due to a similar phenomenon (Cole et al., 1981). Ono noticed concrete structures in Japan showing significant cracking due to deleterious expansion by ASR (Ono, 1988). Swamy reported the failure of airfield pavements in New Zealand due to ASR expansions (Swamy, 1990). Recently, structural damages due to ASR have been identified in Seabrook nuclear power in the USA and Mactaquac Dam in Canada (Saha et al., 2018). Though the fundamental concept of ASR in structural concrete has been known to the scientific community for a few decades, there are still cases of modern structures suffering from severe damage due to this deleterious expansion which confirms the complexity of ASR mechanism (Saha et al., 2018).

As worldwide natural resources become scarce it is increasingly attractive to use recycled concrete aggregate (RCA) as a raw material in new concrete. This topic has been under investigation at the University of Wyoming (UW). Reusing concrete that has been salvaged from demolition work could be a major advancement for concrete structures. A real concern with using RCA as a sustainable building material is its potential for ASR, in particular if the concrete was removed from service due to ASR. As a building material, a full serviceability record is not always available. Hence, effective use of RCA requires the ability to classify whether it is reactive in terms of ASR (Tanner & Fiore, 2015).

1.2 Research Objectives

The objectives of this research are:

- To determine an appropriate level of RCA to be used in new construction.
- To compare independent casting results of CPT to evaluate the adequacy of current ASTM within-laboratory precision statements for RCA.
- To perform a round of testing among ASR researchers to determine if the current CPT precision statements need to be modified to include RCA in this ultra-accelerated test method.

2. LITERATURE REVIEW

2.1 Alkali-silica Reaction

ASR takes place between the reactive silica of aggregates and the alkaline solutions in micro-pores of concrete. The primary sources of alkali are the binder, aggregates and the surrounding environment. Alkalis generated from alkaline metal ions take part in reactions with water to form soluble alkali hydroxides. Silica present in aggregates in the form of quartz is chemically inert. However, any poorly crystalline silica has the affinity to react with water and generate amorphous hydrous silica. Some examples of poorly crystallized silica are opal, chert, chalcedony and glasses; Portlandite ($\text{Ca}(\text{OH})_2$) and calcium silicate hydrate (C-S-H) are produced by the reaction of cement with water in the hydration process. This ($\text{Ca}(\text{OH})_2$) contributes hydroxyl ions (OH^-) into the pore solution (Glasser, 1991; Saha et al., 2018).

From the available literature, ASR only takes place in certain conditions. The four main requirements that must be simultaneously satisfied for the development of ASR in concrete (Bérubé, Duchesne, et al., 2002; Figueira et al., 2019; Rajabipour et al., 2015) are:

- i. the existence of reactive aggregates with concentrations within a critical range i.e., the source of reactive silica.
- ii. high alkali concentration, or more precisely high OH^- ions concentration in interstitial concrete pore solution (for silica attack).
- iii. a source of soluble calcium, such as portlandite, to react with dissolved silica and form the deleterious gel.
- iv. high humidity conditions as the access to moisture allows the gel expansion.

If any of the mentioned factors does not exist then the ASR does not occur (Lindgård et al., 2012) (Gautam & Panesar, 2017). Therefore, all the specifications recommended and mitigation methods to prevent depreciation by ASR seek to exclude at least one of these (Figueira et al., 2019).

2.1.1 Mechanism of Reaction and Expansion

ASR damage is a result of a number of sequential reactions, including: 1) dissolution of metastable silica, 2) formation of nano-colloidal silica sol, 3) gelation of the sol, and 4) swelling of the gel as shown in Figure 2.1. Alternatively, a highly degraded $(\text{SiO}_2)_{\text{solid}}$ may transform directly into $(\text{SiO}_2)_{\text{gel}}$, as long as sufficient but not excessive cross-linking is maintained between silica chains. Among these reactions, silica dissolution is often the slowest (Brantley et al., 2008), and as such, primarily controls the rate of ASR in concrete. Factors that accelerate silica dissolution (e.g., higher alkalinity and temperature) are often used to speed up ASR in concrete, for example in accelerated ASR tests. In addition to silica dissolution, swelling of the gel depends on availability of moisture and mass transport properties of concrete, and could limit the rate of ASR damage in dry and dense concrete (Rajabipour et al., 2015).

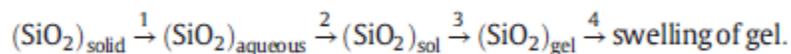


Figure 2.1 Sequential ASR reactions (Rajabipour et al., 2015)

The ASR mechanism consists of three major stages of chemical reaction equations as shown in Figure 2.2. At the initial stage of ASR, the hydroxyl ions undergo reaction with Si-O-Si bonds of amorphous silica to produce silicic acid (OH^-) and alkali silicate (Si-O-R), where (R^+) represents the alkali metal ions. Dissolution products formed include mono-silicic Si (OH)₄ and $\text{Si}_n\text{O}_a(\text{OH})_b$ obligomers, where $2a+b=4n$ (Golmakani, 2017; Iler & Iler, 1979). Those obligomers can easily convert to monomers

(H_2SiO_4^-) and H_3SiO_4^-), di-, tri-, tetra-, and other poly-meric silicate ions (Sjöberg, 1996). Then the silicic acid reacts with the hydroxyl ions (OH^-) and metal alkali that forms alkali silicate hydrate by liberating water and precipitate as C-S-H, C-K-S-H, and C-N-S-H of varying compositions (Bulteel et al., 2002; Saha et al., 2018). The products are hygroscopic, and thus, absorb free water. The less viscous gels may dissipate from the generation site, flow along cracks, and fill pores and voids in the cement paste (Thomas et al., 1991). Finally, the expansion occurs due to hydration of the alkali silicate gel (Glasser, 1991; Ichikawa & Miura, 2007; Swamy, 1992). Excessive expansion can cause cracking of aggregate and cement paste to initiate degradation of concrete (Saha et al., 2018). Thus, ASR manifests as map cracking, pop-outs, and misalignment of structural elements. Examples prevalent around the state are presented in Figure 2.3.

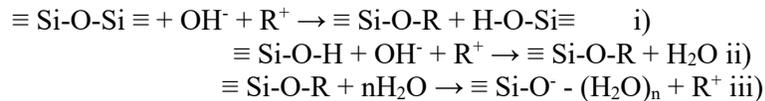


Figure 2.2 Three major stage chemical reactions of ASR (Saha et al., 2018)



Figure 2.3 ASR damage in Wyoming a) map cracking at Federal Street in Riverton and b) pop-outs combined with map cracking in Cheyenne

2.1.2 Effect of Aggregate Characteristics

Aggregates play a significant role in ASR expansion. Depending on the reactivity of aggregates, it can be classified into two categories. Aggregates mostly containing amorphous silica are classified as reactive (e.g. opal, tridymite, cristobalite, acid volcanic glass) and those containing crystalline silica are classified as non-reactive (e.g. chalcedony, cryptocrystalline quartz and strained quartz). The reactive aggregates may also consist of meta-stable crystals, microcrystalline silica and other crystalline forms containing many lattice defects, residual strains, or internal micro-cracks (Vayghan et al., 2016). The reactive aggregates can be found from natural sources as well as from industrial processes as by-products. Furthermore, aggregates from the same rock, may show different potential reactivity (Figueira et al., 2019).

The reactivity of an aggregate also depends on its size. Aggregates with smaller particles give higher surface area that increases ASR expansion (Suwito et al., 2002). However, Poyet et al. found that very small size reactive aggregates could also reduce ASR expansion. This is because very finely ground particles of reactive aggregate may take part in the pozzolanic reaction and reduce alkalinity of the pore solution (Poyet et al., 2007). Bažant & Steffens suggested that the swelling pressure of ASR gel depends on particle diameter. The maximum pressure was observed for particles with the size of 2-3 mm (Bažant & Steffens, 2000). However, Maraghechi et al. argued that ASR expansion increases with the increase of particle size, because larger particles consist of the greater amount of reactive micro-cracks (Maraghechi et al., 2012). Aggregate containing amorphous silica may contribute to concrete strength by pozzolanic

reaction at early ages or may cause ASR expansion at matured ages depending on the size (Saha et al., 2018).

2.1.3 Pessimism Effect

In the last two decades, numerous manuscripts have been focused on the pessimum effect, which is generally described as the balance between the alkali hydroxide concentration of a pore solution and the aggregates reactivity. For the first time it has been showed by Stanton that a definite proportion of certain reactive siliceous aggregate induced the highest concrete expansion (Figueira et al., 2019). Ichikawa confirmed the effectiveness of excessive amount of reactive aggregates above the pessimum proportion can reduce ASR expansion (Ichikawa, 2009). There were two primary reasons behind this phenomenon. Firstly, calcium hydroxide was consumed by the alkali silicates with the increase of reactive aggregates. As a result, formation of the reaction rims was reduced. Secondly, reduction of alkali hydroxides for individual aggregate particles reduced the reaction. Besides, the pessimum proportion for a different type of aggregate can be very hard to predict (Saha et al., 2018).

There is no linear relationship between the potential reactive components in the concrete and the expansion. The pessimum behavior graph can be divided into four regions as shown in Figure 2.4 and described it in Table 2.1. (Hafçı, 2019). Pessimism proportions obviously do not and need not occur at the 50 percent level. If a reactive aggregate has a higher rate of removal of alkalis than the simple case illustrated, each unit increase in reactive constituent will remove a larger proportion of the starting concentration of alkali. This will effectively move the pessimum to the lower alkali content (Swamy, 1992). There are many parameters that exhibit this behavior: “volume fraction, type and size of reactive aggregate, composition of the cement and mixture proportion of the concrete such as water-cement ratio” (Suwito et al., 2002).

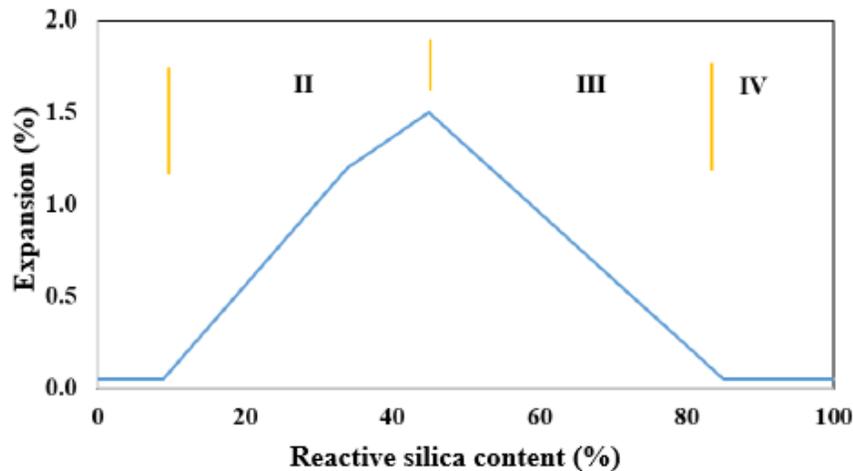


Figure 2.4 Pessimism effect divided into four region (Hafçı, 2019)

Table 2.1 Explanation of pessimum effect regions (Hafçıl, 2019)

Region	Activity	Clarification
I	Reaction starts but cracking does not appear	Gel is not enough to initiate structure damage.
II	Reaction continues, if sufficient reactive silica is available, cracking may start	Expansion is the maximum percent if reactive silica is entirely used up. Alkali/silica ratio may not affect gel composition.
III	Reaction continues, if sufficient reactive silica is available, cracking may start	Expansion does not continue if alkali level is not enough to keep up the reaction. As silica content increase, process of gel expansion starts to decelerate.
IV	Reaction continues but cracking comes to the end	Although reactive silica content is very high and speed of reaction is very fast, gel formation starts to stop due to completion of concrete hardening

2.1.4 Role of Alkali in ASR

Portland cement (PC) is clearly the main source of alkaline in concrete. Cement hydration contributes to a significantly high alkalinity to the pore solution. Therefore, reducing the alkalinity of pore solution is complicated. In addition, lower alkalinity in pore solution can cause carbonation and corrosion of the reinforcement (Saha et al., 2018). Concrete with a high alkali content will have a pH ranging between 13.5 and 13.9, while the concrete with low alkali content will have a pH between 12.7 and 13.1. The high concentration of alkalis optimizes the appearance of ASR due to the increase of OH⁻ concentration and therefore the increase of pH. The risk assessment of ASR linked to alkali content, considering the contribution of sodium and potassium, in PC can be expressed in terms of equivalents of sodium oxide (Na₂O_{eq}) using the equation given in Figure 2.5. Bérubé et al considered that the main cause for the development of ASR was the use of cement with high alkalis content, higher than 0.60 percent Na₂O_{eq} (Bérubé et al., 2004). However, some studies showed alkali contents between 0.45 percent and 0.60 percent of Na₂O_{eq} may react while others showed that contents of 0.40 percent or less rarely did (Figueira et al., 2019).



Where, 0.658 is the ratio between the molecular weight Na₂O & K₂O

Figure 2.5 Equation for equivalent sodium oxide

Alkalis can also be found in both reactive and non-reactive aggregates. Reactive aggregates are those that contain a metastable silica structure that is attacked and dissolved by OH⁻ ions, leading to formation and swelling of ASR gel and ultimately cracking of concrete. Furthermore, even some alkali-containing aggregates that are classified as non-reactive, have been shown to contribute to the alkalinity of concrete pore solution (Rajabipour et al., 2015). It is reported that reactive aggregate such as volcanic aggregates, glass aggregate, and non-reactive aggregates such as granite, mica, zeolites, clay minerals and feldspars can release alkali and increase the pH of pore solution (Lu, Zhou, et al., 2006; Maraghechi et al., 2012; Saha et al., 2018). Grattan-Bellew pointed out that the alkali released from aggregates can be a significant reason behind the ASR expansion of concrete (Grattan-Bellew, 1995). The amount of alkali released from an aggregate depends on its mineral structure. The mechanism of alkali dissolution from the aggregates was attributed to the cation exchange with the calcium hydroxide of pore solution.

It has been observed that there are different types of supplementary cementing materials (SCMs) that contain a significant amount of alkali. Nevertheless, SCMs can reduce the alkalinity of pore solution by alkali binding (Saha et al., 2018). External alkalis may increase expansion due to ASR, especially when concrete is cracked or is highly permeable. Common sources of external alkalis are deicing salts,

seawater, groundwater, and water from industrial processes. In particular, use of pavement deicers can contribute significantly to alkalis. Sodium chloride deicing salt solutions and seawater can provide virtually unlimited amounts of alkali. Certain non-chloride anti-icers and deicers, such as potassium acetate or sodium formate, are currently being investigated regarding their effect on ASR. There are ways to reduce the ingress of external alkalis. In addition to proper handling, placing, and curing of concrete, the use of supplementary cementitious materials and a low water-cementitious materials ratio will reduce concrete permeability, slow the entrance of external alkalis, and reduce potential ASR expansion. Protective coatings and sealers provide a barrier to seawater, deicing salts, and other alkali sources (James & Kerckhoff, 2007).

2.1.5 Role of Calcium

The amount of $\text{Ca}(\text{OH})_2$ has an important role in ASR as the calcium ions (Ca^{2+}) reacts with dissolved silica forming the deleterious calcium-rich ASR gel rim around aggregate particles. Formed by the reactions of cement hydration the Ca^{2+} , whose main source is portlandite, leads to the formation of calcium, sodium and potassium silicate gels of variable composition around the aggregates. These gels absorb water molecules and expand. The swelling caused by this absorption will generate expansive forces and tensile stress causing micro cracking near the reaction site and subsequent expansion and cracking of the concrete (Figueira et al., 2019). A schematic representation of the mechanism of ASR in concrete is presented in Figure 2.6.

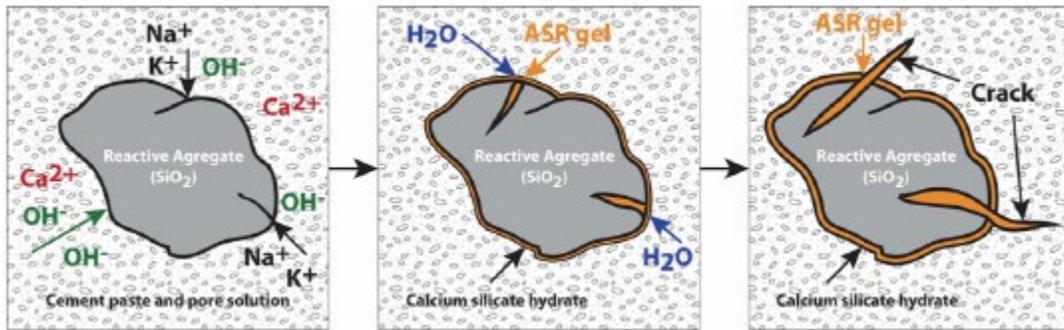


Figure 2.6 Schematic representation of ASR mechanism (Figueira et al., 2019)

The chemical composition of ASR products can be different depending on the location of the gel. For instance, a gel located in pores and cracks contains a higher amount of calcium as compared to the gel in the reactive aggregates. Therefore, it is difficult to correlate the chemical composition and the expansion of ASR products (Fernandes, 2009; Saha et al., 2018). Vayghan et al. (Vayghan et al., 2016) found significant expansion for sufficient concentration of the calcium in a binder matrix. The authors explained that viscosity and yield strength of ASR gel increased due to the presence of calcium. As a result, greater stress was caused by the gel expansion. However, Leemann et al. (Leemann et al., 2011) demonstrated that the water binding capacity of ASR gel not only depends on calcium content but also on calcium to silicon ratio (Ca/Si). According to their study, ASR gel bound water both physically and chemically. The amount of physically bound water is considerably higher than the amount of chemically bound water. Figure 2.7 shows that both the physically and chemically bound water gradually decreased with the increment of the Ca/Si ratio.

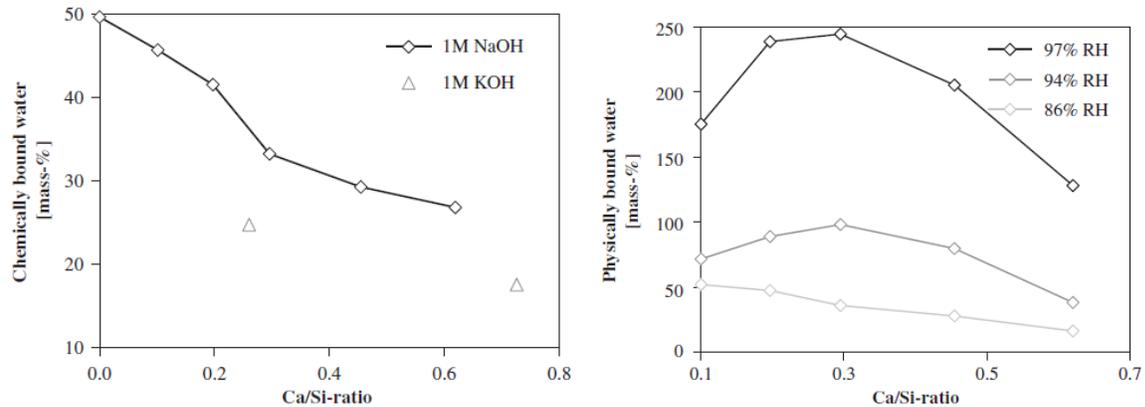


Figure 2.7 Water binding capacity by ASR gel with respect to molar Ca/Si ratio (Leemann et al., 2011)

2.1.6 Effect of Moisture

Water appears to have a double effect on ASR; as reactive agent since it influences the rate of expansion at the time of formation of the reaction product and as transport agent of different reactive species. Reducing the exposure to water may constrain or halt the reaction and expansion. However, the expansion will re-develop at a rapid pace when the concrete has retained the necessary relative humidity (Oberholster & Davies). For ASR development concrete must be exposed to high humidity, over 80–85 percent RH and the ASR should not occur when the concrete is exposed to low humid conditions, even with highly reactive aggregates. The expansion by ASR is not necessarily dependent on water ingress. Instead, the expansion due to ASR may occur as a result of the moisture inside the concrete. This idea is supported by the appearance of cracking in dry areas compared to permanently immersed areas. However, once the reaction has occurred and enough gel has formed, any increase in the humidity may lead to quick expansion and then to cracking, that is why wetting-drying cycles can endanger a structure (Bérubé & Fournier, 1993; Figueira et al., 2019; Hobbs, 1988; Larive et al., 2000).

All concrete structures are susceptible to ASR excepting the ones where the concrete, by itself, can control the internal humidity to values lower than 80 percent and that are permanently protected from the atmospheric conditions and other sources of moisture (Figueira et al., 2019).

2.1.7 Preventive Measures of ASR

As mentioned in section 2.1 the preventive measures of ASR seek to exclude at least one of the four requisites (e.g. source of reactive silica, high alkalis concentration, a source of soluble calcium and high humidity). The following sections will discuss in detail the main achievements on how to control each requirement:

- ***Limiting the alkali content of concrete:*** The control of the alkali content assumes that the manufacturers and/or suppliers of cement certify the average alkali content and its variability. This measure is already used in several countries as part of the concrete control and standardization process. In addition to cement, other sources of alkalis for concrete such as pozzolan additions, aggregates, kneading water and additives should be considered. The reduction of the alkali content of the interstitial concrete pore solution can be performed by: (i) controlling the alkali content in concrete by limiting the content of concrete soluble alkalis or using suitable binders; (ii) using a total alkali content < 0.60 percent $\text{Na}_2\text{O}_{\text{eq}}$; and (iii) mineral addition to the concrete (Figueira et al., 2019; Lindgård et al., 2012). According to the ASTM C150, 0.60 percent $\text{Na}_2\text{O}_{\text{eq}}$ is accepted as the maximum limit for cement to be used with reactive aggregates

and is an optional limit when concrete contains deleteriously reactive aggregate (ASTM-C150, 2001; Figueira et al., 2019).

- Use of non-reactive aggregate: Not all aggregates are susceptible to ASR. So, non-reactive aggregates (e.g. those producing less than 0.04 percent expansion in ASTM C1293 (ASTM-C1293, 2009) test or less than 0.01 percent expansion in ASTM C1260 (ASTM-C1260, 2014)) can be used to avoid severe ASR problem (Rajabipour et al., 2015).
Concrete moisture control: As mentioned previously a certain content of RH (above 80 percent) is necessary to initiate ASR in concrete. Multon and Toutlemonde have shown that if the water is supplied, regardless of the age of an ASR damaged structure, it swells if the ASR gel is already produced (Multon & Toutlemonde, 2010). The authors also proposed that the ASR reaction could have been stopped by lack of water in certain areas of the structure. Therefore, any methodology that restrains the water access to the concrete with reactive aggregates mitigates the risk of ASR development. These include, for instance, equipment or project solutions that avoid the accumulation of water. Allowing water to drain away from the concrete structure should be considered (Figueira et al., 2019). Bérubé et al. tested the behaviour of different sealant materials in ASR mitigation namely silane, oligosiloxane, polysiloxane, linseed oil, or epoxy resin on specimens prepared with a w/c = 0.50 exposed to different conditions (Bérubé, Chouinard, et al., 2002). The authors showed that all the specimens, sealed early with silane, oligosiloxane, or polysiloxane did not expanded considerably nor showed map-cracking pattern. The epoxy resin was not effective and samples sealed with linseed oil showed poorer results compared to silane-based sealers. Therefore, a good sealer may provide improved aesthetic appearance and stop the ASR expansion of the concrete specimens (Figueira et al., 2019).
- Use of lithium compounds: The use of lithium salts to prevent ASR was reported for the first time by McCoy and Caldwell in 1951 (McCoy & Caldwell, 1951). The authors tested over 100 different compounds, including organic products, metallic salts, acids and adjuvants and reported that the lithium compounds were the most effective. Three main lithium compounds emerged as candidates for controlling ASR: LiOH, LiCO₃ and LiNO₃ (Rajabipour et al., 2015). The mechanisms proposed to explain the effectiveness of lithium compounds against ASR are not fully understood and several mechanisms have been proposed (Figueira et al., 2019). Several mechanisms were postulated by which lithium compounds may control ASR; lithium a) may reduce the dissolution rate of silica, b) may impede formation of alkali-silica gel, c) may reduce repulsive forces between the colloidal gel particles of ASR, thus reducing swelling, and d) may incorporate into the alkali-silica gel, altering its properties and expansion (Rajabipour et al., 2015).
- Use of supplementary cementitious materials (SCMs): SCMs primarily reduce the alkalinity (pH) of pore solution by OH⁻ consumption and alkali binding, consume portlandite, and reduce permeability and mass transport of concrete, all due to the pozzolanic reaction. Using a sufficient quantity of SCM is the most common method of ASR mitigation for new structures. SCMs with low CaO and low alkali contents have been shown to be the most effective (Rajabipour et al., 2015). Numerous workers have shown that SCMs have a significant impact on the concentration of alkalis in the pore solution. Figure 2.8 shows the OH⁻ concentration at 2 years as a function of the level of SCM. Silica fume is the most efficacious SCM in this role, at least initially, followed by metakaolin, low-calcium fly ash and slag. High-calcium or high-alkali fly ashes are less effective and have to be used at relatively high levels of replacement to produce a significant reduction in the pore solution alkalinity (Thomas, 2011). It has been suggested that a minimum of 15 percent class F fly ash, 30 percent class C ash, 25 percent slag, 5 percent silica fume cement replacement or lithium admixtures will be effective to mitigating ASR problems (James & Kerckhoff, 2007).

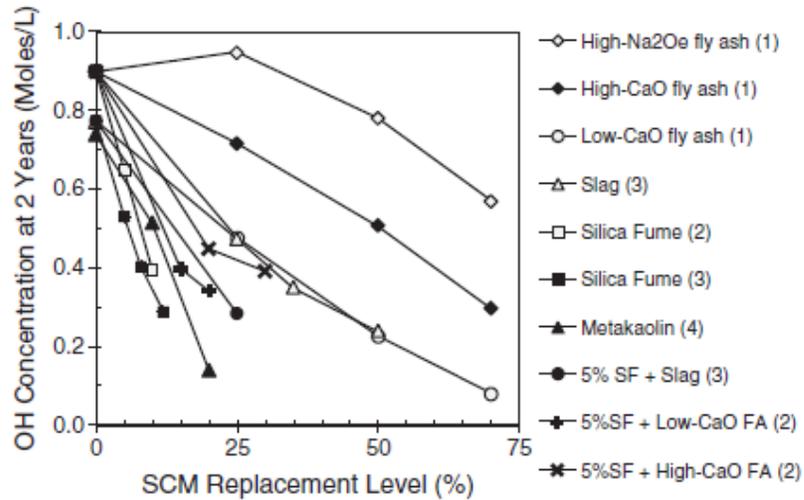


Figure 2.8 Effect of SCM type and replacement level on the pore solution OH⁻ concentration at 2 years (Thomas, 2011)

2.2 Recycled Concrete Aggregate

Every year, around 20 billion tons of concrete is used globally and this amount is increasing daily (Mehta & Meryman, 2009). This increasing demand for concrete has increased the consumption of coarse and fine natural aggregates, which account for around 70 percent of the total concrete volume in a concrete mix (Mefteh et al., 2013; Xie et al., 2018). Meanwhile, the rapid urbanization witnessed in recent years has also resulted in an extensive increase in the rate of demolition of old structures, prompted by the limited availability of new construction sites. This in turn has led to the generation and release of large amounts of construction and demolition (C&D) wastes. About 510 million tons of construction and demolition waste are produced each year in Europe, while the United States and Japan produce respectively about 325 and 77 million tons of such materials annually. Given that China and India are now producing and using over 50 percent of the world's concrete, their waste generation will likely keep increasing as development continues (Beauchemin et al., 2018). These wastes account for a large part of solid waste in most countries across the world and are commonly and ineffectively disposed of in landfills at significant cost, resulting in the depletion of landfill space (Behera et al., 2014; Torgal & Jalali, 2011; Xie et al., 2018). As the demand for sustainable construction practices increases, more of an emphasis is being placed on recycling waste concrete instead of disposing of the material in landfills. Reusing waste concrete as recycled concrete aggregate (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 can reduce the amount of transportation required to bring aggregates from a source location to a concrete-making facility (Adams et al., 2013).

For instance, most countries have incorporated some recycling plan with varied success. Japan takes the leading edge of sustainably managing concrete waste by producing very little and recycling up to 98 percent. This is a product of minimal land for landfilling and an ever-increasing scarcity in natural aggregate. However, the most important reason is the country's governmental intervention which mandated improving to a 90 percent recycling rate (Rao et al., 2007; Tam, 2009). About 68 percent of the concrete waste in the United States is recycled, most of which is used as road base (Goonan, 2000). Only 6 percent of the RCA that is recycled in the United States is used as aggregate in new concrete, with the remaining RCA being used as riprap, as fill, in hot-mix asphalt, or in other applications (Adams et al., 2013; Goonan, 2000).

2.2.1 Properties of Recycled Aggregate

Recycled concrete aggregate could be produced from (a) recycled precast elements and cubes after testing, and (b) demolished concrete buildings. Whereas in the former case, the aggregate could be relatively clean, with only the cement paste adhering to it, in the latter case the aggregate could be contaminated with salts, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals. It has been shown that contaminated aggregate after separation from other waste, and sieving, can be used as a substitute for natural coarse aggregates in concrete (Nagataki et al., 2004; Rao et al., 2007). An RCA particle consists of two phases: the original natural aggregate and the adhered mortar. The original natural aggregate is the coarse aggregate that was used in the creation of the parent concrete. Adhered mortar consists of cement paste and the original 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 (Adams et al., 2013). As with natural aggregate, the quality of recycled aggregates also needs to be assessed before using the aggregate. Some of the important properties of such recycled aggregate are discussed in the following sections.

2.1.1.1 Density, Porosity and Water Absorption

Residual adhered mortar on aggregate is a main factor affecting the properties of density, porosity, and water absorption of RCA. The density of RCA is generally lower than natural aggregate density, due to the adhered mortar that is less dense than the underlying rock (McNeil & Kang, 2013). Limbachiya et al. showed that the relative density of RCA (in the saturated surface dry state) is approximately 7–9 percent lower than that of natural aggregate (Limbachiya et al., 2000). Porosity and water absorption are related aggregate characteristics, also attributed to residual mortar. Natural aggregate generally has low water absorption due to low porosity, but the adhered mortar on RCA has greater porosity which allows the aggregate to hold more water in its pores than natural aggregate. In general, the porosity of RCA is up to 12 percent higher depending on the amount of adhered mortar and the aggregate size. Subsequently, the absorption capacity of RCA has been found to be up to 8 percent points higher than that of natural aggregates (Adams et al., 2013; Katz, 2003). The aggregate characteristics of density, porosity, and water absorption are a primary focus in determining the proper concrete mix. These characteristics limit the absorption capacity of aggregates to no more than 5 percent for structural concrete, and thus the proportion of RCA is often limited to 30 percent in concrete mixes (Etxeberria et al., 2007; McNeil & Kang, 2013).

2.1.1.2 Shape and Size Distribution

The shape of the aggregate pieces is influential on the workability of the concrete. Natural aggregate is generally an angular shape with smooth sides (McNeil & Kang, 2013). Sagoe-Crentsil et al. described the plant-produced RCA as grainy in texture and has a more rounded, spherical shape which seemed to improve workability (Sagoe-Crentsil et al., 2001). The residual mortar on RCA can smooth out the hard edges of the original aggregate. This allows the new mortar to flow better around the aggregate. Generally, a series of successive crushing and subsequent removal of impurities are used to achieve desirable grading of RCA (Rao et al., 2007). Standards for concrete aggregate define a range within which the gradation of aggregate must lie in order to be acceptable aggregate for structural concrete. It was found that the gradation curves of coarse RCA were within this specified range (McNeil & Kang, 2013; Sagoe-Crentsil et al., 2001).

2.1.1.3 Abrasion Resistance

Crushing and Los Angeles (L.A.) abrasion tests are measures of the durability of aggregate material on its own. There is a general trend that RCA has higher values for crushing and L.A. abrasion than natural aggregate, meaning when the aggregate is contained and crushed or impacted by steel balls in the L.A. abrasion test RCA has more fine particles break off than natural aggregate. The behavior of RCA in crushing and abrasion tests demonstrates the weakness of the adhered mortar. Since this layer is most likely to break off than the aggregate itself, it is predicted that the adhered mortar layer may also create a weak connection within concrete (McNeil & Kang, 2013).

2.2.2 Properties of Concrete Made with RCA

Concrete mixes using RCA can be designed in much the same way as those using natural aggregate. The extra absorption is appropriately accounted for when determining the unit water content. Rao et al. summarized some recommendations for proportioning of RCA as given below (Rao et al., 2007):

- When designing a concrete mix using recycled aggregate of variable quality, a higher standard deviation should be employed in order to determine a target mean strength based on a required characteristic strength.
- When coarse recycled aggregate is used with natural sand, it may be assumed at the design stage, that the free w/c ratio required for a certain compressive strength will be the same for RCA as for conventional concrete.
- For a recycled aggregate mix to achieve the same slump, the free water content will be approximately 5 percent more than for conventional concrete.
- The sand-to-aggregate ratio for RCA is the same as when using NA.
- Trial mixes are mandatory and appropriate adjustments depending upon the source and properties of the RCA should be made to obtain the required workability, suitable w/c ratio, and required strength of concrete.

2.1.1.4 Workability and Air Content

Due to water absorption by recycled aggregates, moisture conditioning of coarse recycled aggregates is needed in order to maintain the right workability. Figure 2.9 showed that the RCA used in saturated-surface-dry (SSD) conditions improve the concrete workability (Mefteh et al., 2013). The workability loss, in terms of slump loss appears fast in the early minutes when aggregates are in contact with water and decrease after 30 min. Besides, Sagoe-Crentsil et al. found that plant processing of RCA produces relatively smoother spherical particles, which leads to improved concrete workability in comparison with natural aggregate concrete with equivalent grading and ratio of fine to coarse aggregate (Sagoe-Crentsil et al., 2001). Rao reported that the workability of RCA for the same water content in the concrete is lower especially when the replacement levels exceed 50 percent (Rao et al., 2007).

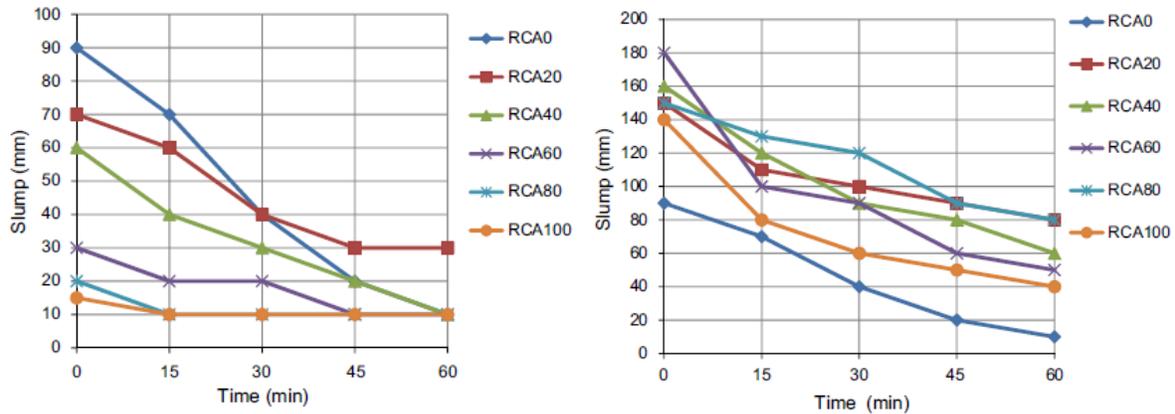


Figure 2.9 Changes of slump of concrete mixes for RCA a) dry condition and b) SSD condition (Mefteh et al., 2013)

The concrete air content is greatly influenced by its mortar volume. RCA influences the concrete air content because it has a larger mortar content. The air content of the fresh concrete containing RCA is slightly more variable and often up to 0.6 percent higher than the air content of the fresh natural aggregate concrete (NCA). The entrained and entrapped air in the reclaimed mortar of RCA causes this variation. Hence, the air content of the existing mortar should be considered while deciding the target air content of RCA concrete (Safiuddin et al., 2013).

2.1.1.5 Compressive Strength

Though researchers have reported a reduction in strength in RAC, it should be noted that the extent of reduction is related to the parameters such as the type of concrete used for making the RCA (high, medium or low strength), replacement ratio, water/cement ratio, and the moisture condition of the recycled aggregate (Rao et al., 2007). Most research recommended that, without changes to the mix involving adjustments to the w/c ratio, up to 25 or 30 percent of coarse aggregate can be replaced with RCA before the ceiling strength is compromised (Limbachiya et al., 2000; McNeil & Kang, 2013). Figure 2.10 shows trends for compressive strengths for three RCA fractions as they vary with w/c ratio (McNeil & Kang, 2013). The data for 30 percent RCA follows that of 0 percent RCA for almost every w/c ratio tested, while the 100 percent RCA data lie at compressive strength values below that of 0 or 30 percent RCA by about 5 N/mm² (725 psi). At the lowest w/c ratios, the compressive strengths for mixes with RCA become more dissimilar to conventional concrete (McNeil & Kang, 2013). Etxeberria et al. found similar behavior with tests using 25 percent RCA that performed as well as conventional concrete with the same w/c ratio (Etxeberria et al., 2007). The authors tested concrete made with 0, 25, 50, and 100 percent coarse RCA concrete mixes and concluded that up to 25 percent could be replaced without significant change in compressive strength or a different w/c ratio. However, to obtain the same strength with 50–100 percent RCA, w/c ratio needed to be 4–10 percent lower, and without this alteration, the compressive strength for 100 percent RCA mixes was reduced by 20–25 percent (Etxeberria et al., 2007; McNeil & Kang, 2013).

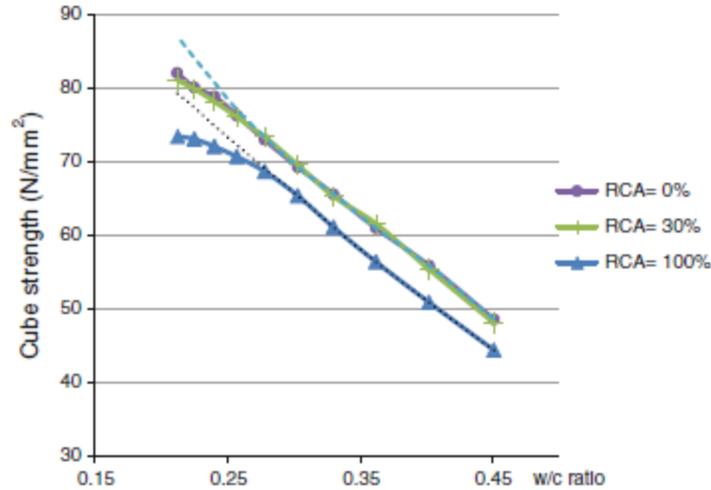


Figure 2.10 Concrete compressive strength versus water/cement ratio for RCA contents (McNeil & Kang, 2013)

2.1.1.6 Splitting Tensile Strength

Splitting tensile strength is less affected by RCA content than compressive strength. Several past and recent tests show that the splitting tensile strength of RCA concrete is comparable to conventional concrete. In some cases, RCA concrete performed superior to NCA with regards to tension (McNeil & Kang, 2013). According to Etxeberria et al., the improvement is due to the increased absorption of the mortar attached to the recycled aggregate and the effective interfacial transition zone (Gucunski et al.), which indicates a good bond between aggregate and the mortar matrix (Etxeberria et al., 2007). While this residual mortar creates a weakened spot for compressive failure to occur, limited quantities improve the tensile capacity by creating a smoother transition between mortar and aggregate. Thus, unlike with compressive strength, high-strength concrete mixes with low w/c ratios show even greater improvement in splitting tensile strength (McNeil & Kang, 2013). In contrast, Safiuddin et al. reported that the splitting tensile strength of RCA concrete is lower than that of NCA concrete (Safiuddin et al., 2013), as shown in Figure 2.11.

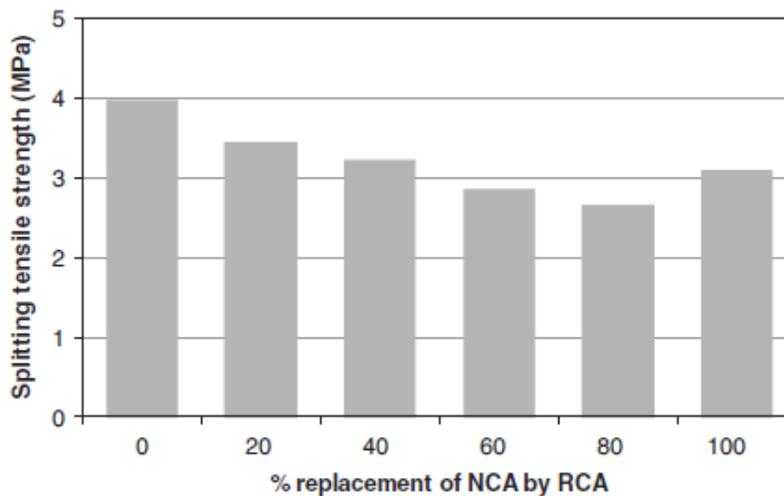


Figure 2.11 Effect of RCA on the splitting tensile strength of concrete (Safiuddin et al., 2013)

2.1.1.7 Modulus of Elasticity

The modulus of elasticity of the recycled aggregate concretes is reduced when the recycled aggregates percentage is increased (Safiuddin et al., 2013), as shown in Figure 2.12. This situation is expected, because recycled aggregates are more prone to deformation than raw aggregates. Besides recycled concrete aggregate has lower modulus than natural aggregate and the modulus of concrete depends significantly on the modulus of the aggregates (Etxeberria et al., 2007). Froudinstou-Yannas found that the modulus of elasticity for RCA concrete was as low as 60 percent of that of NA concrete (Froudinstou-Yannas, 1977).

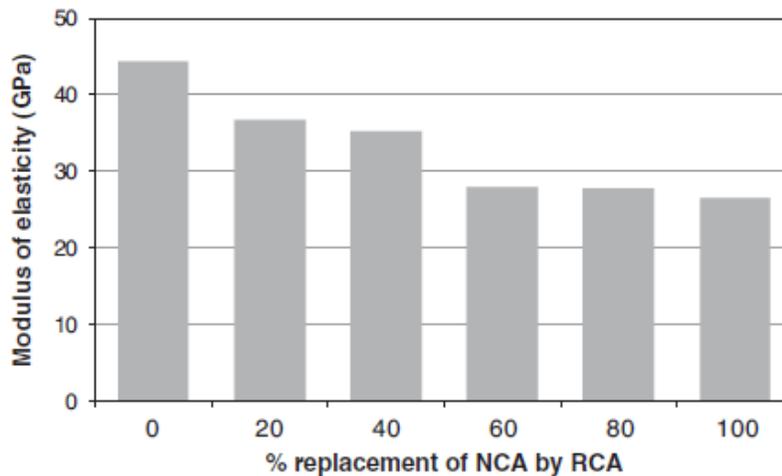


Figure 2.12 Effect of RCA on the modulus of elasticity of concrete (Safiuddin et al., 2013)

2.1.1.8 Permeability

The permeability of concrete depends on both the absorption capacity of the included aggregate and the permeability of the concrete matrix (cement or binder paste). The permeability of concrete is also affected by its porosity and the size, distribution, and continuity of the pores. RCA permeability appears to be higher than that of NCA concrete for the same water to cement ratio. The permeability of RCA concrete can be 200–500 percent higher than that of NCA concrete (Safiuddin et al., 2013). If properly accounted for in design, RCA concrete mix can be engineered to have a similar permeability as that of NCA concrete (Safiuddin et al., 2013; Tam & Tam, 2007).

Safiuddin et al. summarized the ranges of changes in the hardened properties of concrete due to RCA in comparison to natural aggregate (Safiuddin et al., 2013), as presented in Table 2.2.

Table 2.2 Effect of RCA on the hardened properties of concrete
(Safiuddin et al., 2013)

Property	Range of changes
Dry density	5–15% less
Compressive strength	0–30% less
Splitting tensile strength	0–10% less
Flexural strength	0–10% less
Bond strength	9–19% less
Modulus of elasticity	10–45% less
Porosity	10–30% more
Permeability	0–500% more
Water absorption	0–40% more
Chloride penetration	0–30% more
Drying shrinkage	20–50% more
Creep	30–60% more
Thermal expansion	10–30% more

2.2.3 The Potential Alkali-silica Reactivity of RCA

With respect to ASR in recycled concrete, it became more complicated since ASR in RCA concrete is affected by many factors due to the variety, inhomogeneity, production procedures and using conditions of RCA. The variety of RCA originates from the original aggregates with different alkali reactivity and the extent of ASR (Adams et al., 2013; Beauchemin et al., 2018; Johnson & Shehata, 2016; Peng et al., 2020). Production procedures involving different crushing stages could result in RCA with different size, density, residual mortar content and adhesion to the original cement paste, which could also affect the ASR performance of recycled concrete. The conditions of RCA such as the alkali content of cement used in recycled concrete, the pre-washing of RCA and the water saturation of RCA have also affected the ASR of recycled concrete (Peng et al., 2020; Shehata et al., 2010). All the above factors have been often combined in recycled concrete, which made the ASR performance of recycled concrete and the correlation with their parent concrete performance more complicated.

In contrast to the original aggregate, RCA consists of five different materials that have unique mechanical properties containing aggregate, mortar matrix, adhered mortar, new Interfacial Transition Zone (ITZ) (Gucunski et al.), and old ITZ as shown in Figure 2.13 (Jayasuriya et al., 2018). Generally, original aggregate accounts for 65-70 percent by the volume of RCA and the remaining part is residual mortar. The presence of residual mortar can also release some alkalis into pore solution (Peng et al., 2020). Beside this, there might be alkalis in the RCA that comes from parent concrete that was exposed to deicing salts might contain higher levels of alkalis than natural aggregates and increase the risk of ASR (Adams et al., 2013).

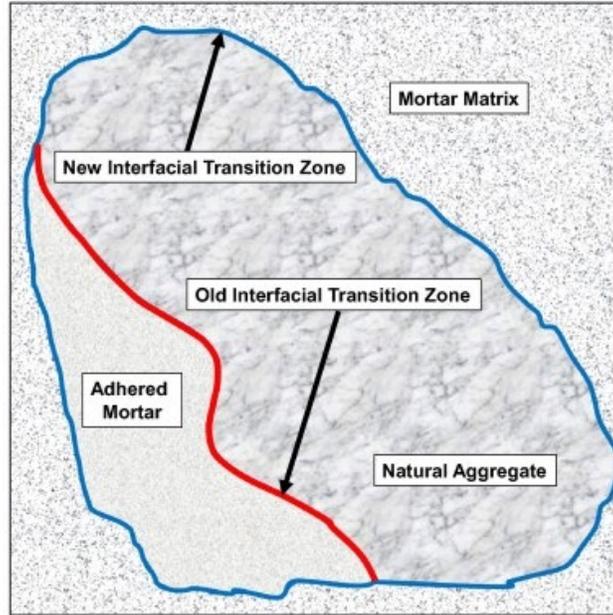


Figure 2.13 Schematic diagram of recycled concrete aggregate (Jayasuriya et al., 2018)

Despite the inconsistent observations, in principle the extent of ASR in RCA concrete seems to be mainly controlled by the content of alkali reactive component available to reaction. If the reactive original aggregate had been largely consumed in original concrete, the potential of ASR would be limited in recycled concrete (Peng et al., 2020). This was reflected by the observation of lower ASR expansion for the RCA concrete than for the original aggregate concrete in several studies (Johnson & Shehata, 2016; Shehata et al., 2010). Figure 2.14 shows that the ASR performance of RCA concrete is closely related to the origin of RCA (Johnson & Shehata, 2016). The ASR expansion of RCA and original aggregate concrete made from four types of aggregates shows that the RCA concretes exhibit lower ASR expansion than that of the corresponding original aggregate concrete. For the RCA concretes, the ASR expansion is higher when the original aggregate has high alkali reactivity. For instance, Alberta and Spinghill natural aggregate have high alkali reactivity; therefore, the ASR potential of their corresponding RCA is higher in comparison to the RCA made from Bernier or Potsdam concrete at similar replacement level of RCA as shown in Figure 2.14.

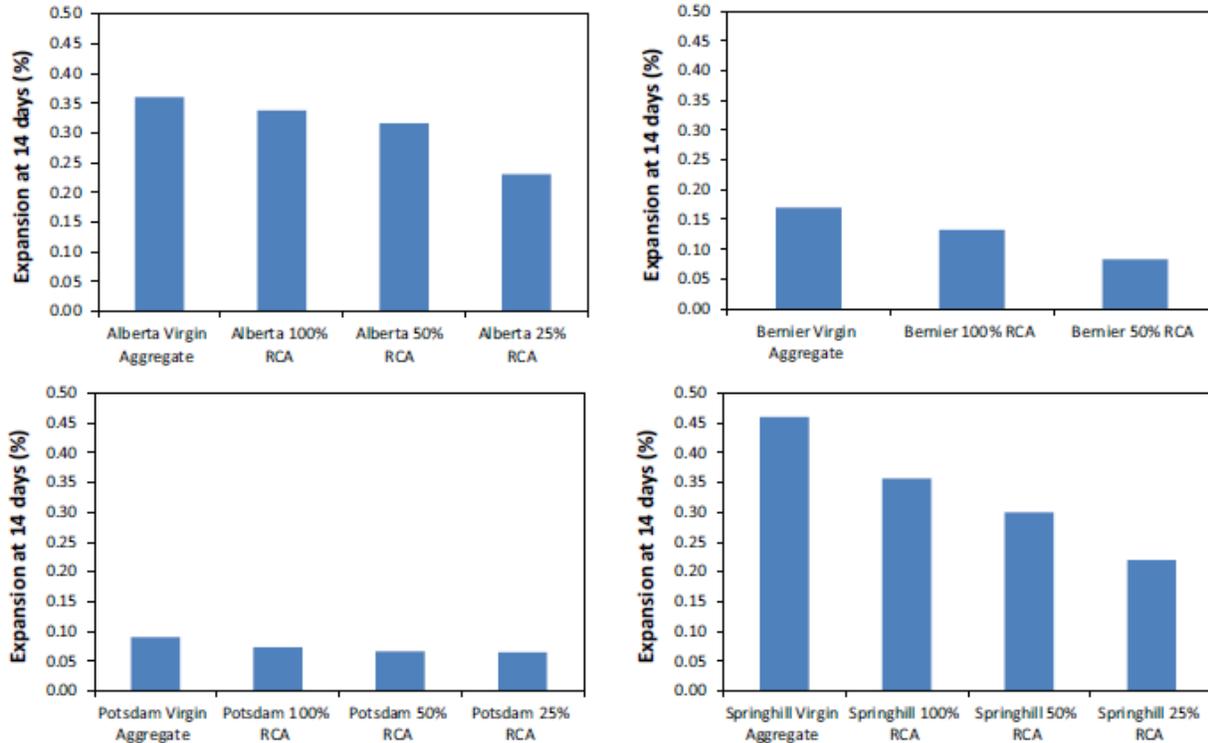


Figure 2.14 Expansion of original aggregate with various sources and RCA generated from concrete containing the same aggregate (Johnson & Shehata, 2016)

2.3 Precision Statement

A standard test method prescribes a fixed set of equipment requirements, measurement methodologies and procedural protocols on how to produce a measurement for a specific property of interest. In a perfect world, if the same material is repeatedly tested using the same test method, whether by the same operator in the same laboratory using the same apparatus or by different laboratories and operators using different apparatus meeting the specified requirements, all measurements generated will be numerically identical. However, we do not live in a perfect world. Repeated execution of the same test method on the same material, whether by the same operator in the same laboratory using the same apparatus or by different operators in different laboratories using apparatus of similar design, will not always yield numerically identical results. Minor differences will exist between test results due to variations in factors that are inherent in the test method. Variation attributable to factors considered inherent in the test method is generally referred as common-cause variation and can be thought of conceptually as the inherent imperfections associated with the test method. In statistical nomenclature, this inherent imperfection is known as *precision* although some might prefer to think of it as *imprecision*. (Lau, 2009).

A statement of precision allows potential users of a test method to assess in general terms the test method's usefulness with respect to variability in proposed applications. A statement of precision is not intended to exhibit values that can be exactly duplicated in every user's laboratory. Instead, the statement provides guidelines as to the magnitude of variability that can be expected between test results when the method is used in one, or in two or more, reasonably competent laboratories. So, the precision of a measurement process, and hence the stated precision of the test method from which the process is generated, is a generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated. The measurement process must be in a state of statistical control; else the precision of the process has no meaning. The greater the

dispersion or scatter of the test results, the poorer the precision. Measures of dispersion, usually used in statements about precision, are, in fact, direct measures of imprecision (ASTM-E177, 2008).

The need to develop accurate precision statistics is important to evaluate if a set of data is valid. The precision of measurements can be explained into three kinds; a) within-laboratory precision or repeatability of test method, b) intermediate precision, and c) between-laboratory precision or reproducibility of test method. Table 2.3 outlines three different sets of specific conditions associated with those precision as defined in ASTM E177. In this project repeatability and reproducibility of test method have been evaluated for RCA autoclave test with the participation of six laboratories. Beside these, the within-laboratory precision from repeated experiments has been evaluated for RCA CPT with independent casting by three operators on different days.

Table 2.3 Conditions for precision. (Adopted from [ASTM-E177, 2008; Lau, 2009])

Precision	Conditions			
	Laboratory	Operator	Apparatus	Location
Within-laboratory	Same	Same	Same	Same
Intermediate	Same	Different	Same	Same
Between-laboratory	Different	Different	Different	Different

A variety of standards exist related to inter-laboratory experiments and preparing statements of precision for each test method and material used (ASTM-C670, 2015; ASTM-C802, 2014; ASTM-E177, 2008; ASTM-E691, 2018). For example, ASTM C670 specifically addresses the preparation of precision and bias statements, while ASTM E177 defines the use of the terms precision and bias in ASTM methods. ASTM Practice E691 explains how an inter-laboratory study should be performed in order to obtain viable and broadly applicable precision statements. It recommends between six and 30 laboratories to adequately profile the population using at least three materials representing different test levels, with six or more being preferable for broadly applicable precision statements be used. For physical tests, three or four replicates are suggested to adequately profile each material. ASTM C802 specifically addresses conducting an inter-laboratory study to develop precision statements for construction materials.

3. MATERIALS

3.1 Aggregates

RCA materials were collected from an ASR damaged slab located at the WYODOT Materials Laboratory located in Cheyenne. The slab was around 25 years old and cast with highly reactive Knife River (KR.) aggregates. Sample images from collecting the RCA are illustrated in Figure 3.1. RCA aggregates were crushed to get equal amounts of 1/2 in, 3/8 in and #4 retained aggregates. The aggregates passed through #4 sieve were collected as RCA fine aggregate. But the fine aggregates seemed more like the adhered mortar paste that was around the aggregates which was not similar to the natural fine aggregate. In addition, the gradation of RCA fine was not within the ASTM C33 limits (ASTM-C33, 2018) which is shown Figure 3.2. On the other hand, the coarse RCA aggregates is closer to raw aggregate as the adhered mortar from the coarse aggregate was mostly removed through crushing, sieving and washing process. Because of these reasons, this study replaced RCA coarse aggregate only in different percentages. Brighton (BT) coarse and fine aggregates were used as non-reactive aggregate.



Figure 3.1 Process of collecting RCA aggregates

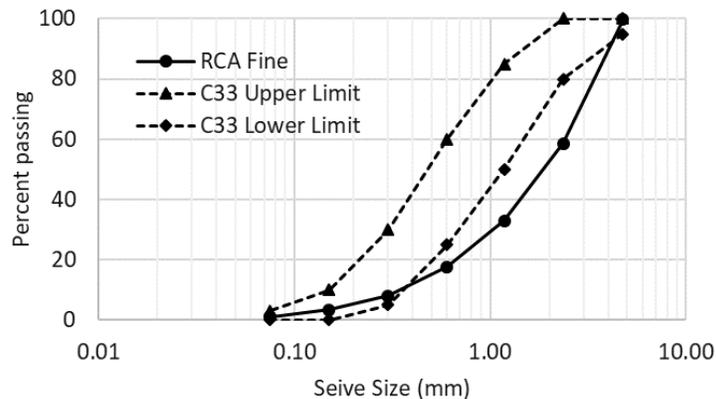


Figure 3.2 RCA fine aggregate gradation curve not falling within the ASTM C33 limits

After receiving the aggregates, the sieving of aggregates is completed using a mechanical screen shaker, shown in Figure 3.3, to get the required gradation for all ASR tests. CPT tests uses as delivered fine aggregate with a gradation that meets ASTM C33 limits (ASTM-C33, 2018). The nonreactive BT fine aggregates had an as received gradation that meets C33 (Figure 3.4).



Figure 3.3 Mechanical screen shaker

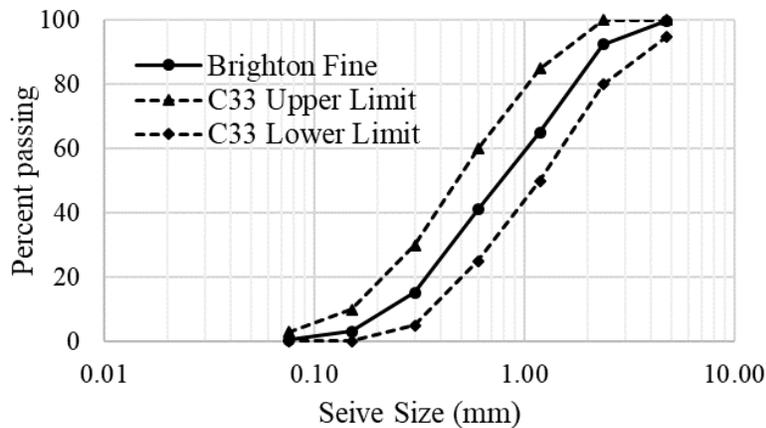


Figure 3.4 Gradation of Brighton fine aggregate meets ASTM C33 requirements

All the aggregates for the ASR investigations tests were washed after completion of sieving. Two washing frames were built to expedite washing aggregates. Washing of coarse aggregate was completed by loading the aggregates on the top of the inclined platform and running water over them until the water ran clear as shown in Figure 3.5a. Fine aggregates were washed by placing a No. 200 sieve tray in one of the slots below the inclined washing platform and spraying water until clear water ran as shown in Figure 3.5b. After washing, the aggregates were dried at 230 degrees F (110 degrees C) for 24 hours. Then the oven dried aggregates were stored in shelves till casting.



Figure 3.5 Washing process a) coarse aggregates and b) fine aggregates

The physical properties of washed aggregates were determined following ASTM C29, C127 and C128 standards (ASTM-C29, 2016; ASTM-C127, 2015; ASTM-C128, 2015). The summary of the physical properties of both BT and RCA aggregates are presented in Table 3.1.

Table 3.1 Physical properties of aggregates

Properties	Coarse aggregate		Fine aggregate
	BT	RCA	BT
Apparent Specific Gravity	2.61	2.62	2.70
Bulk Specific Gravity (Dry)	2.57	2.34	2.64
Bulk Specific Gravity (SSD)	2.59	2.45	2.66
Absorption (%)	0.62	4.49	0.76
Dry-rodded Unit Weight (lb/ft ³)	103.5	89.6	106.8

3.2 Cement

The high alkali cement came from Mississauga, Ontario in Canada is used in this research. Two shipments of the high alkali cement were received, one in 2017 and another in 2019. The chemical composition of each shipment is indicated in Table 3.2. The bolded section $\text{Na}_2\text{O}_{\text{eq}}$ is the governing factor when determining the total alkalis available in the cement paste matrix. The value is determined by: percent Na_2O + 0.658 times percent K_2O .

Technical grade NaOH pellets were purchased from the chemical stockroom and used to boost the alkalinity of field specimens and to meet the alkalinity requirements of CPT and ACPT prisms.

Table 3.2 Chemical composition of high alkali cements

Chemical	Cement	
	2017 shipment	2019 shipment
Silica Oxide (SiO ₂) (%)	19.2	20.5
Alumina Oxide (Al ₂ O ₃) (%)	5.3	5.5
Iron Oxide (Fe ₂ O ₃) (%)	2.7	2.3
Calcium Oxide (CaO) (%)	61.8	61.6
Magnesium Oxide (MgO) (%)	2.4	2.4
Sulphur Trioxide (SO ₃) (%)	4.0	4.0
Total Alkali (Na₂O_{eq}) (%)	0.90	0.98
C ₃ S (Adjusted) (%)	51	40
C ₂ S (Adjusted) (%)	15	25
C ₃ A (Adjusted) (%)	9	11
C ₄ AF (Adjusted) (%)	8	7

4. TEST METHODS

4.1 General

Ever since Stanton (1940) reported his discovery of alkali-silica reaction in California, there has been keen interest in laboratory tests to (1) predict whether a given aggregate will cause expansion and cracking in concrete and (2) to evaluate preventive measures to allow for safe use of those aggregates found to be potentially reactive. Stanton was not only the first to discover ASR in field structures, but he was also the first researcher to develop a test method to assess aggregate reactivity, and he used this technique to also evaluate the use of pozzolans to control ASR-induced expansion. The method developed by Stanton, which is essentially the same as the current ASTM C 227 test method, is still in use today by some researchers and practitioners, but a wide variety of test methods have been developed and implemented since the time of Stanton's pivotal research on ASR. Some of these test methods have been successful, some have proven to be complete failures, and others fall somewhere in the middle. Through research and development, as well as trial and error, test methods have evolved over the years, and there has been a general convergence in terms of the tests that are generally used (Thomas et al., 2013).

At present, many test methods are available in the literature for assessing the alkali-reactivity of concrete aggregates. Some test methods are based on the direct analysis of aggregates, such as chemical methods and petrographic examination. Other test methods are based on the expansive behavior of cement–aggregate combinations, such as the mortar bar expansion test or concrete prism expansion test (Bavasso et al., 2020). It should be mentioned that development of a perfect ASR test for predicting the exact performance of concrete in the field is not done yet. Field structures can be exposed to variable and fluctuating conditions with different temperature cycles, moisture availability, loading, loads of restraint, and external ionic sources. It should not be expected that a rapid test exists that can simulate all these conditions, have a low inter-laboratory coefficient of variation, and give information on long-term field performance. With that being said, current test methods could still be improved to more rapidly and reliably identify more aggregate or aggregate-cement combinations (Golmakani, 2017).

Tomas et al summarized the attributes for an ideal test as follows (Thomas et al., 2006):

- The test should be reliable in terms of predicting how the combination of materials will behave under field conditions.
- The test should use the reactive aggregate (or the combination of aggregates) under consideration rather than a standard reactive aggregate.
- The test should not involve excessive processing of the aggregate (such as crushing a coarse aggregate to allow it to be tested in mortar).
- The test should be capable of evaluating the contribution of the cement alkalis rather than requiring an increase in the level of alkali.
- The test should be rapid, providing results in weeks or months rather than years.
- The test should be capable of assessing all types of SCM, lithium compounds and combinations of SCM and lithium (with cements of different alkali level).

None of the tests currently used for evaluating preventive measures for ASR meets all of the criteria. In terms of reliability, the concrete prism test offers the best prediction of field performance with high-alkali cement and reactive aggregates. Its main shortcoming is the length of time required to run the test (Thomas et al., 2006). The following sections will cover the test methods used in this study with discussion on the procedures, advantages and limitations of each.

4.2 Concrete Prism Test (CPT)

There are a number of different concrete prism tests used to identify reactive aggregates or evaluate preventive measures, but most of them are similar to the extent that elevated temperature and augmented cement alkalis are used to accelerate the reaction (Thomas et al., 2006). The CPT was first standardized in Canada in the 1950s and is now designated as CSA A23.2-14A. The test method was originally published in the United States as ASTM C1293 in 1995 and has been revised and reapproved most recently in 2015. In RILEM AAR-3, the CPT uses slightly different test parameters and a different recommended expansion limit (Wood, 2017).

There are two types of CPTs that are explored in this project: with different RCA percent replacement and with independent castings. This test, as defined by ASTM C1293, is carried out over one year for normal concrete specimens and two years for concrete specimens containing SCMs. The test uses three 3 x 3 x 11.25 inch (75 x 75 x 285 mm) prisms with a water-to-cement ratio between 0.42 and 0.45. Concrete is cast with a cement content of 707.94 lb/yd³ (420 kg/m³). The cement is required to have an equivalent alkali content between 0.8 percent and 1.0 percent, and additional alkalis (NaOH) then are added to the mixing water to obtain a total alkali content of 1.25 percent (by mass of cement). Once the fresh concrete is prepared, four CPT prisms were cast along with three 4 x 8 inch (100 x 200 mm) cylinders according to the ASTM C192 and C1293 (ASTM-C192, 2016; ASTM-C1293, 2009). The additional fourth specimen was prepared for redundancy. The prisms within the molds are kept covered with wet towels and wrapped with a non-absorbent plastic sheet to prevent any moisture loss before demolding. The CPT molds without and with prisms and prevention of moisture loss are illustrated in Figure 4.1 and Figure 4.2, respectively.



Figure 4.1 CPT molds a) without prisms and b) with prisms



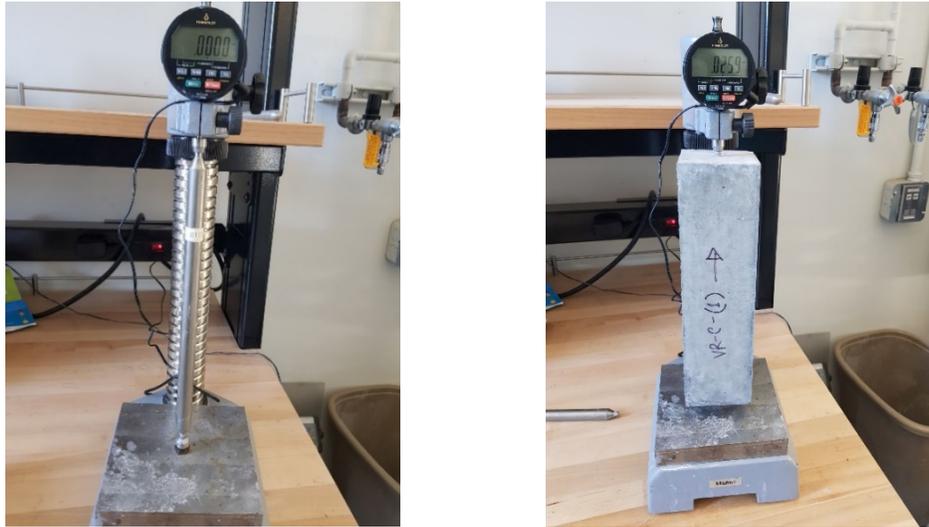
a) Prisms covered with wet towels



b) Molds wrapped with plastic sheet

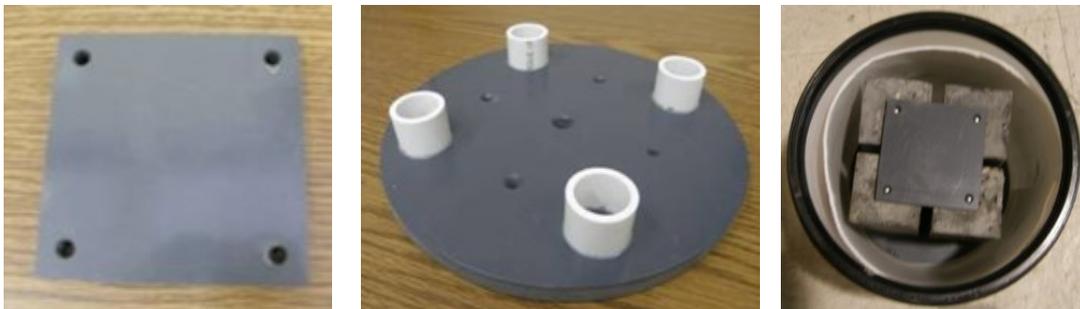
Figure 4.2 Prevention of moisture loss before demolding

After 24 hours of casting the prisms are demolded and initial readings are measured using a length change comparator as shown in Figure 4.3. Then the prisms are placed into 5-gallon buckets over approximately 1 inch (25 mm) of water using the bottom rack to achieve more than 95 percent relative humidity. A top mold is also used to secure and separate the specimens. A wicking fabric lines the inside of the bucket to help maintain the desired humidity constant. A screw top lid is used to seal the bucket and trap the moisture. A storage container with the supporting racks can be seen in Figure 4.4.



a) Comparator with reference bar b) Comparator with prisms

Figure 4.3 CPT measurement



a) Top rack b) Bottom rack c) Prisms inside bucket

Figure 4.4 Storage container with supporting racks

The prisms inside the buckets are stored in the oven at 100 ± 3.2 degrees F (38 ± 2 degrees C) as displayed in Figure 4.5. The oven is 12 x 8 x 8 ft (3.66 x 2.44 x 2.44 m) box made, inside the structural lab at High Bay research facility, with OSB (Oriented standard board) plywood on the outside and foam insulation on the inside. The building process of the oven are illustrated in Figure 8.1 in Appendix A. A temperature controlled space heater is used to maintain a constant temperature, and two fans are used to circulate the air within the room. To measure CPT expansion after specified times the prisms are brought out of the buckets and wrapped with the wet towels and put into the alternative curing chamber for 16 ± 4 hours as shown in Figure 4.6. The expansion limit for the CPT is 0.04 percent at one year to classify the aggregate as potentially deleteriously reactive aggregate. If supplementary cementitious materials (SCMs) are used, the limit is 0.04 percent after two years.



Figure 4.5 CPT prism storage oven a) outside and b) inside



Figure 4.6 CPT prisms in alternative curing chamber

4.3 Autoclaved Concrete Prism Test (ACPT)

An autoclave is a pressure vessel used to create a pressurized, high-temperature environment well in excess of ambient temperatures and pressures. Steam autoclaves are used to raise the internal temperature of the concrete or mortar specimens in order to accelerate the alkali-silica reaction. Additionally, an alkali hydroxide is commonly added to the mixing water in ASR testing to facilitate the reaction by ensuring a sufficient supply of both alkalis and hydroxides. This is also done in the CPT, usually to a lesser degree (Wood, 2017). A number of autoclave test methods have been developed for ASR testing, most notably those by Ming-Shu et al., Tamura, Nishibayashi et al., Fournier et al., Nishibayashi et al., and Giannini & Folliard (Fournier et al., 1991; Giannini & Folliard, 2013; Ming-Shu et al., 1983; Nishibayashi et al., 1996; Nishibayashi et al., 1987; Tamura, 1987). Some of those methods demonstrated promise, but none have come into wider use or been standardized. The test parameters of each of these methods are summarized and compared in Table 4.1 (Wood, 2017).

Table 4.1 Comparison of autoclave test methods for ASR (Wood, 2017)

Test Parameter	Chinese Method (1983)	GBRC (1987)	Nishibayashi et al. (1987)	Laval/CANMET (1991)	Nishibayashi et al. (1996)	ACPT (2013)
Duration (from mixing)	3 days	3 days	2 days	2 days	unknown	4 days
Duration of Conditioning	6 hours	2 hours	4 to 5 hours	5 hours	4 hours	24 hours
Specimen Type	Mortar	Mortar	Mortar	Mortar	Concrete	Concrete
Specimen Size, mm	10 x 10 x 40	40 x 40 x 160	40 x 40 x 160	25 x 25 x 285	75 x 75 x 400	75 x 75 x 285
w/cm	0.30	unknown	0.45	0.50	0.54	0.42
Na ₂ O _{eq} , by mass of cement	1.5%	2.5%	1.5%	3.5%	3.0%	3.0%
Temperature	150 °C	111 °C	128 °C	130 °C	133 °C	133 °C
Conditioning	In 10% KOH solution inside autoclave	In boiling water inside pressure vessel	Inside autoclave	Inside autoclave	Inside autoclave	Inside autoclave
Proposed Limit	-	-	-	0.15%	-	0.08%

Although not a new concept, the use of autoclaving to quickly determine aggregate alkali-silica reactivity has been mostly limited to testing fine aggregates in mortar specimens rather than using concrete. One of the limitations of using only fine aggregate in mortar is some coarse aggregates perform differently when crushed into fine aggregates (Lu, Fournier, et al., 2006; Wood, 2017). The autoclaved concrete prism test (ACPT), was developed at The University of Texas at Austin with the goal of expediting ASR testing in concrete specimens while providing results that relate to field performance and CPT results (Wood, 2017). This research focuses primarily on extension of the ACPT test previously performed in the University of Wyoming and the University of Alabama. The autoclave is shown in Figure 4.7.

**Figure 4.7** Autoclave a) exterior and b) interior with prism

This test follows the same procedure as the standard CPT with the following exceptions:

- Total alkalis are raised to 3.0 percent.
- Specimens cure another 24 hours after demolding.
- An initial measurement is made at this point.
- Prepare the autoclave with deionized water to create steam environment.
- The specimens are placed in an autoclave for 24 ± 3 hours at 29 psi (0.2 MPa) with the temperature set at 133 degrees C.
- After the specimens are autoclaved, the specimens are cooled from approximately 194 degrees F (90 degrees C) to 73.4 degrees F (23 degrees C) over about 40 minutes by submerging them in 194 degrees F (90 degrees C) water and running cool water through the tank. This was achieved by placing a five-gallon bucket full of water with its lid on into the oven at 194 degrees F (90 degrees C) to have hot water of 194 degrees F (90 degrees C) ready before the autoclave get open.
- The final measurement is taken once the prisms are cool.

5. RESULTS AND DISCUSSION

5.1 CPT Tests Using RCA

Five sets of specimens (four prisms in each set) were tested using 0, 20, 30, 40 and 50 percent RCA replacements of coarse aggregate following ASTM C1293. The one-year test results are illustrated in Figure 5.1 and summarized with coefficients of variation (CV) in Table 5.1. The data are presented in Table 8.1 of Appendix . The legend BT-Control indicates with 0 percent RCA replacement and RCA-20, 30, 40 and 50 respectively indicate 20, 30, 40 and 50 percent RCA replacement of coarse aggregate. Results indicate that percentage expansion increases with increasing RCA replacement. This is because the original aggregate of RCA was highly reactive aggregate and with the addition of RCA aggregate total reactive silica content increases. But all the RCA expansion, moderately reactive, are less than the original virgin aggregate expansion, highly reactive, which indicates using RCA in new construction are not as susceptible to the original virgin aggregate. Figure 5.2 shows the comparative compressive strength with the replacement of RCA aggregate in different percentage. It was observed that the compressive strength decreases with the increase of RCA replacement and the highest strength reduction was about 7 percent for RCA-50. These findings are similar to those by Etxeberria et al., Rao et al., and Safiuddin et al (Etxeberria et al., 2007; Rao et al., 2007; Safiuddin et al., 2013).

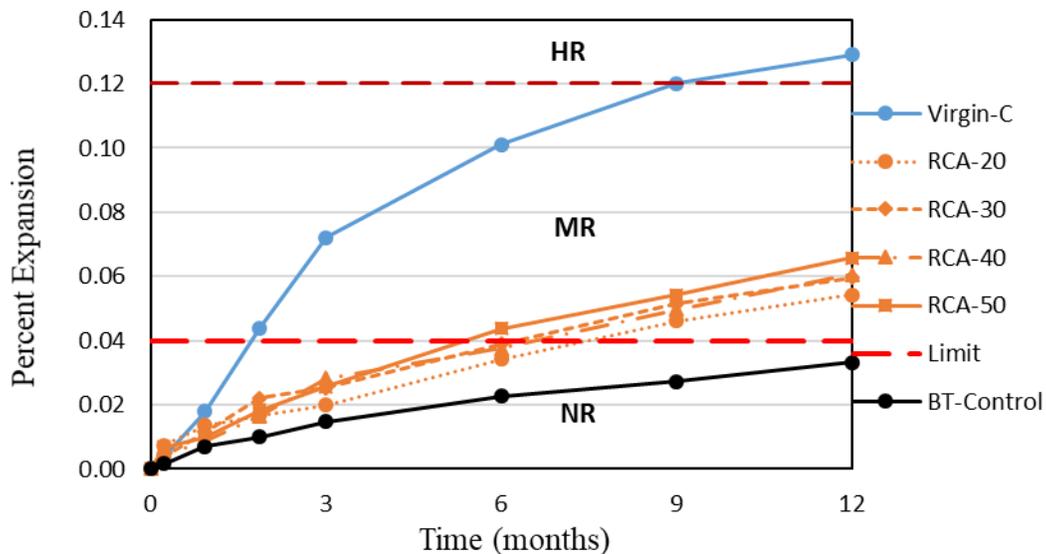


Figure 5.1 CPT results for RCA aggregates

Table 5.1 One-year CPT expansions for RCA aggregates

RCA aggregates	Expansion (%)	CV (%)
BT-Control	0.033	8.98
RCA-20	0.054	13.58
RCA-30	0.060	5.23
RCA-40	0.061	12.11
RCA-50	0.066	5.47

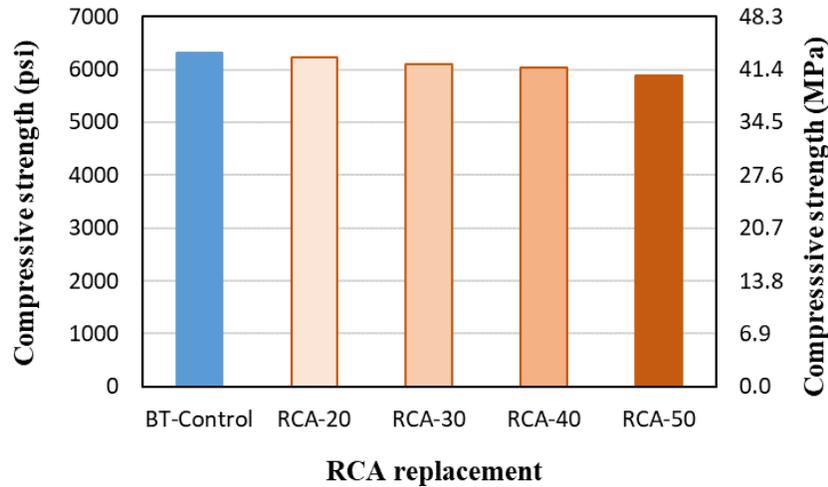


Figure 5.2 Compressive strength comparison with RCA aggregate

5.2 CPT Tests to Evaluate Within-laboratory Precision Using RCA

CPT tests with 20 and 50 percent RCA replacement were performed by three laboratory operators (J1, J2, F1, F2, Z1, Z2) for a total of 12 batches. The three operators cast the prisms independently with same mixture design and cured them in the same oven but a single operator took the measurements over the exposure duration. The test results are illustrated in Figure 5.3 and Figure 5.4 with data compiled in Table 8.2 and Table 8.3 of Appendix . The CPT results provide higher expansion for RCA-50 than RCA-20 for all of specimens. Summary of RCA CPT results and within-laboratory precisions are presented in Table 5.2. The coefficient of variations (CVs) for RCA-20 and RCA-50 are 10.3 and 5.9 percent respectively at one year exposure. ASTM C 1293 limits the of coefficient of variation for within-laboratory precision to 12 percent for the average expansions greater than 0.02 percent (ASTM-C1293, 2009). So, testing of RCA aggregate in CPT by different operators does not require any further modification on ASTM within-laboratory precision statement.

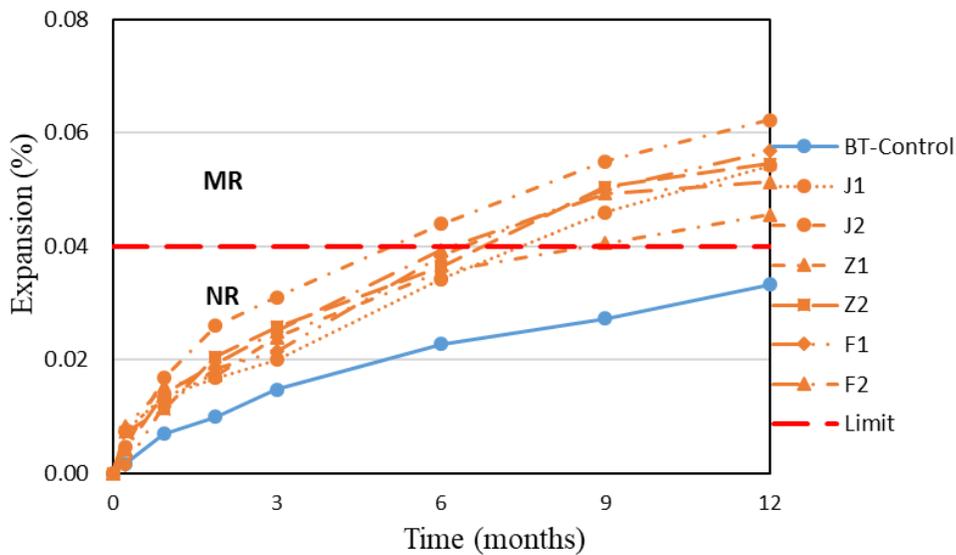


Figure 5.3 CPT results variations for RCA-20

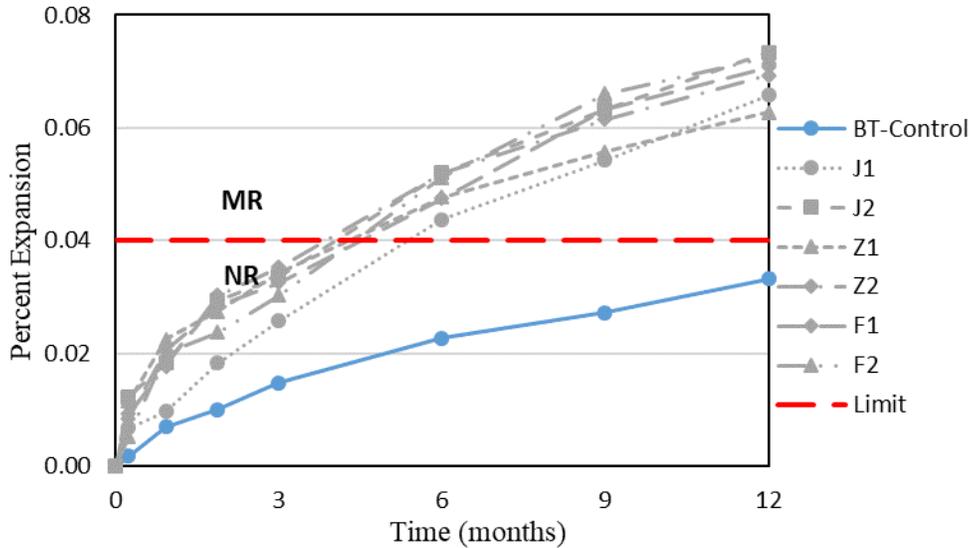


Figure 5.4 CPT results variations for RCA-50

Table 5.2 Summary of RCA CPT results and within-laboratory precisions

Batch	Average expansion (%)	Standard Deviation	CV (%)	Allowable CV (%)	Remarks
RCA-20	0.054	0.0056	10.3	12	Meets (10.3<12)
RCA-50	0.069	0.0041	5.9	12	Meets (5.9<12)

5.3 Autoclave Tests with Varying Levels of RCA

A total of five batches (four concrete prisms in each batch) were tested in the autoclave using 0, 20, 30, 40 and 50 percent RCA replacement of coarse aggregate. The autoclave test results are shown in Figure 5.5 and summarized in Table 5.3. Here the results indicate that percentage expansion decreases with increasing RCA replacement which is opposite to the nature of CPT results. One possible explanation for this behavior might be the increased volume of adhered mortar and old interfacial transition zone, that occurs with higher percentages of RCA replacement as depicted in Figure 2.13. A slight decrease in expansion pattern is observed with the increased RCA replacement within the short curing period of 24 hours in autoclave. A simple linear relationship ($y = -0.00049x + 0.160$) between the average percent expansion and percent RCA replacement was obtained for the autoclave test as shown in Figure 5.6. Here the negative slope results in a decrease in expansion of 0.00049 percent with a 1 percent increase in RCA replacement; the R^2 value (95.6 percent) indicates a very good agreement with data. Finally, within the set of four specimens that make up each data point, the percent CV varies from 2.89 to 6.77 percent which is still within the allowable limit of 12 percent according to ASTM 1293.

For a relative comparison between the autoclave test and CPT, Figure 5.7 is presented along with the trend lines. This indicates that RCA aggregates opposite exhibit linear expansion behavior with slight negative slope within the very short test duration (24 hours of curing) for the ultra-accelerated test in compare to the CPT test which has a positive slope. An accelerated mortar bar testing (AMBT) completed by Johnson & Shehata (Johnson & Shehata, 2016), indicates an increase in expansion with increasing RCA percentage for in the accelerated mortar bar test, indicating another positive slope.

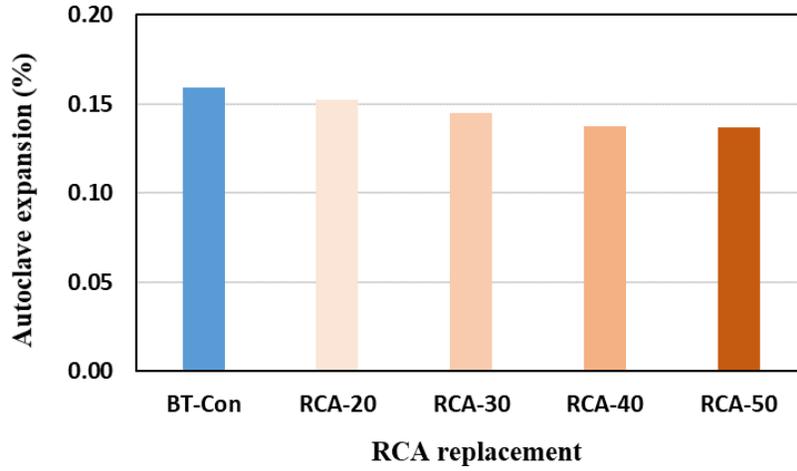


Figure 5.5 RCA autoclave test results

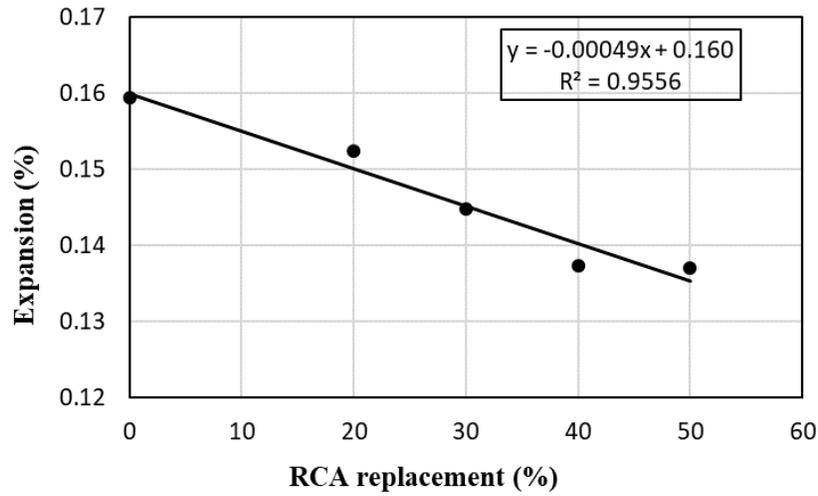


Figure 5.6 Linear relationship between percent expansion and percent RCA replacement

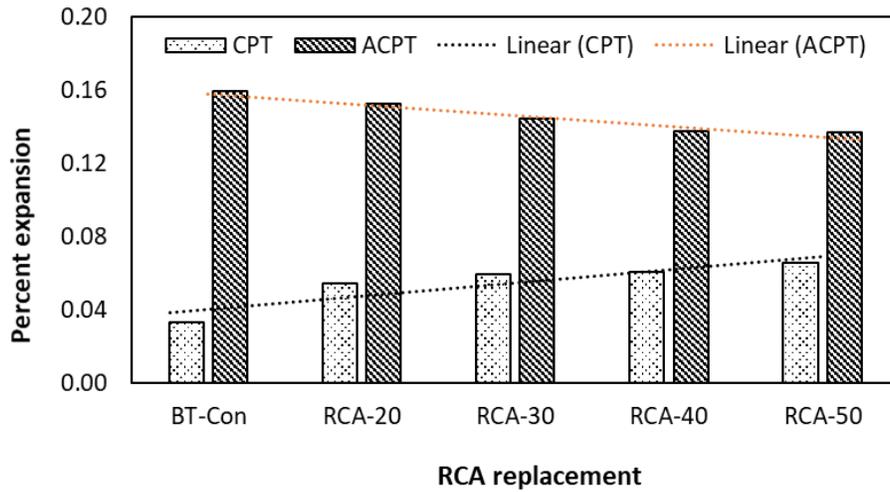


Figure 5.7 Comparison of CPT and autoclave expansion

Table 5.3 RCA autoclave test results

RCA aggregates	Expansion (%)	CV (%)
BT-Control	0.159	6.77
RCA-20	0.152	2.89
RCA-30	0.145	5.00
RCA-40	0.137	4.31
RCA-50	0.137	5.23

5.4 Autoclave Tests for Multi-laboratory Study

5.4.1 Multi-laboratory Precision

Two batches (20 and 50 percent RCA replacement) of prisms for seven independent laboratories with experience testing ASR, were subject to a regimen of accelerated curing. Five laboratories tested at least three prisms for each batch whereas two laboratories tested one prism for each batch due to using a smaller autoclave. The comparison of test results from these seven laboratories are illustrated in Figure 5.8 and summarized in Table 5.4. Five out of the seven laboratories found higher expansion for RCA-20 than RCA-50 for ACPT test. The coefficient of variations (CVs) for RCA-20 and RCA-50 are 15.17 and 19.24 percent, respectively. Both limits are within the allowable limit of 23 percent for multi-laboratory precision.

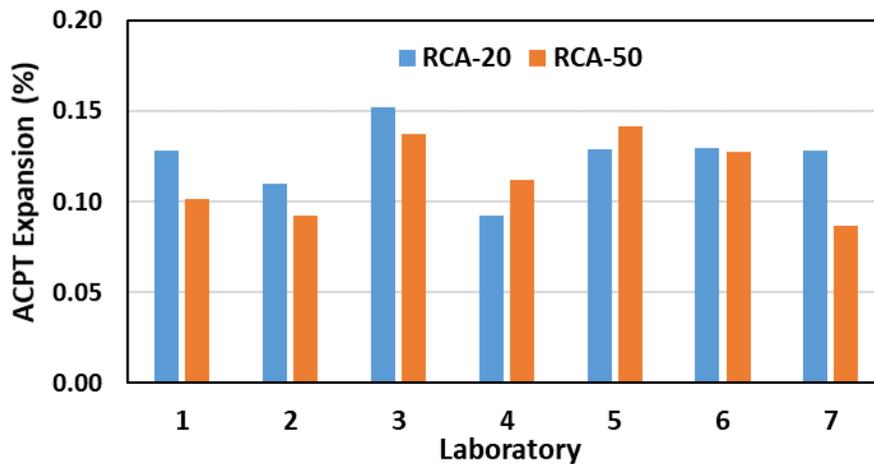


Figure 5.8 ACPT results of seven laboratories

Table 5.4 RCA autoclave results of six laboratories with precisions

Laboratory	Average expansion (%)	
	RCA-20	RCA-50
1	0.128	0.101
2*	0.110	0.092
3	0.152	0.137
4	0.092	0.112
5	0.129	0.142
6	0.130	0.127
7*	0.124	0.086
CV (%)	15.17	19.24
Allowable CV (%)	23	23
Remarks	Meets (15.17<23)	Meets (19.24<23)

**tested one specimen for each batch based on autoclave size*

5.4.2 Consistency Statistics

Consistency statistics are performed in this project to analyze and identify any data that does not statistically fit with all the other data. Additionally, these statistics give an overall feel for the variability of the test method. For an inter-laboratory study, these statistics are performed in two manners: between-laboratory consistency (h) and within-laboratory consistency (k). ASTM E691 defines variables k and h to evaluate sets of data in inter-laboratory studies. A higher k value indicates greater within-laboratory variability and lower k value indicates smaller within-laboratory variability. Similarly, h value indicates for between-laboratory variability. The h and k consistency statistics need to fall within the critical values: if they do not, then the test for that particular laboratory needs further investigation. The critical values for h depend on number of the laboratories and the critical values for k depend both on the number of laboratories and on the number of replicate test results. The inter-laboratory study worksheet for RCA-20 and RCA-50 are presented in Table 5.5 and Table 5.6. Here the critical h and k values are ± 2.05 and 1.92 respectively and both h and k values are within this limit.

Table 5.5 Inter-laboratory worksheet for RCA-20 (according to ASTM E691)

Lab Number	Test results, x			Cell average, \bar{x}	Cell Standard deviation, s	Cell deviation, $d = (\bar{x} - \bar{\bar{x}})$	$h = d/s_{\bar{x}}$	$k = s/s_r$
	1	2	3					
1	0.134	0.124	0.126	0.128	0.0056	0.003	0.16	1.54
2	0.110	-	-	0.110	-	-0.015	-0.78	-
3	0.155	0.150	0.157	0.154	0.0033	0.029	1.49	0.92
4	0.088	0.094	0.093	0.092	0.0033	-0.033	-1.70	0.92
5	0.127	0.130	0.134	0.130	0.0032	0.005	0.28	0.88
6	0.132	0.134	0.132	0.133	0.0014	0.008	0.40	0.38
7	0.128	-	-	0.128	-	0.003	0.16	-

Average of cell averages, $\bar{\bar{x}} = 0.125$ Standard deviation of cell avg., $s_{\bar{x}} = 0.0196$ Repeatability Standard deviation, $s_r = 0.0036$ Between-Laboratory standard deviation, $s_L = 0.0195$ Reproducibility standard deviation, $s_R = 0.0198$ **Table 5.6** Inter-laboratory worksheet for RCA-50 (according to ASTM E691)

Lab Number	Test results, x			Cell average, \bar{x}	Cell Standard deviation, s	Cell deviation, $d = (\bar{x} - \bar{\bar{x}})$	$h = d/s_{\bar{x}}$	$k = s/s_r$
	1	2	3					
1	0.099	0.115	0.090	0.101	0.0129	-0.013	-0.58	1.66
2	0.092	-	-	0.092	-	-0.022	-1.00	-
3	0.129	0.141	0.142	0.137	0.0072	0.023	1.05	0.92
4	0.114	0.103	0.119	0.112	0.0081	-0.002	-0.09	1.04
5	0.141	0.142	0.142	0.142	0.0008	0.028	1.26	0.10
6	0.132	0.126	0.124	0.127	0.0041	0.013	0.62	0.53
7	0.086	-	-	0.086	-	-0.028	-1.26	-

Average of cell averages, $\bar{\bar{x}} = 0.114$ Standard deviation of cell avg., $s_{\bar{x}} = 0.0219$ Repeatability Standard deviation, $s_r = 0.0078$ Between-Laboratory standard deviation, $s_L = 0.0215$ Reproducibility standard deviation, $s_R = 0.0228$

The h and k consistency statistics are plotted by laboratories in Figure 5.9 and Figure 5.10. The h-plot indicates how the laboratory average property values for each material compare with the overall average for that material. Figure 5.9 shows that the h values for both RCA-20 and RCA-50 in all the participating laboratories are within the critical limit (± 2.05). No further investigation is required for any laboratory. A positive h value indicates the average value of the test result of the corresponding laboratory and material is greater than the overall average test result of all participating laboratories for that material. And the negative h value explains the opposite scenario. On the other hand, higher h value indicates high standard deviation for the corresponding laboratory and material. Hence lower h values are better than high h values.

The k-plot compares the single-operator variability among the laboratories and k-values are always positive. The primary pattern to look for is whether a laboratory has large (or small) k-values for all or most of the materials. Elimination of that laboratory from the analysis may result in a set of data with

similar k-values for the remaining laboratories. High k-values represent high single-operator variability (ASTM-C802, 2014). Hence lower k values are better than high k values. A check for outliers is used to examine the data for the particular laboratory-material combination. Figure 5.10 shows that the k values for both RCA-20 and RCA-50 in all the participating laboratories are within the critical limit (1.92). No further investigation is required for any laboratory. As two laboratories tested only one specimen, k value is not found for those laboratories. Among other five laboratories, laboratory 1 has highest k values indicating highest variability and laboratory 6 found least variability as it has the lowest k value.

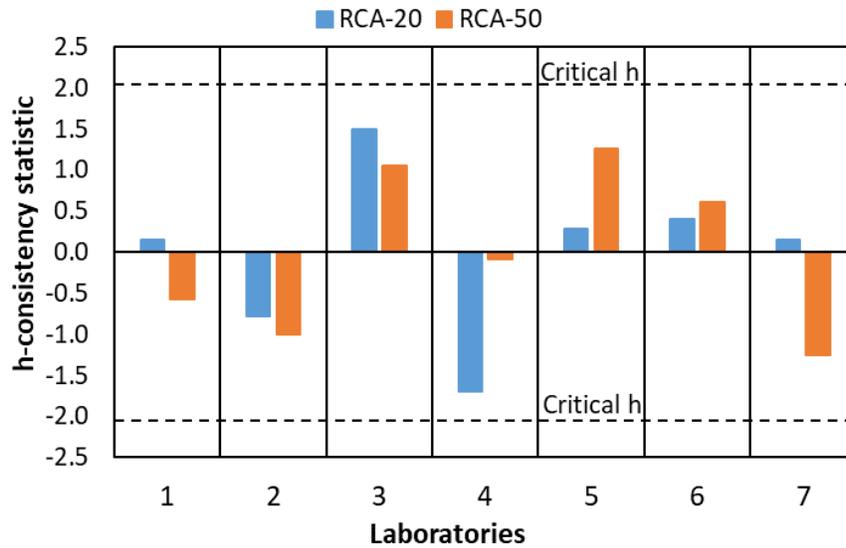


Figure 5.9 Between-laboratory consistency statistics, h, by laboratories

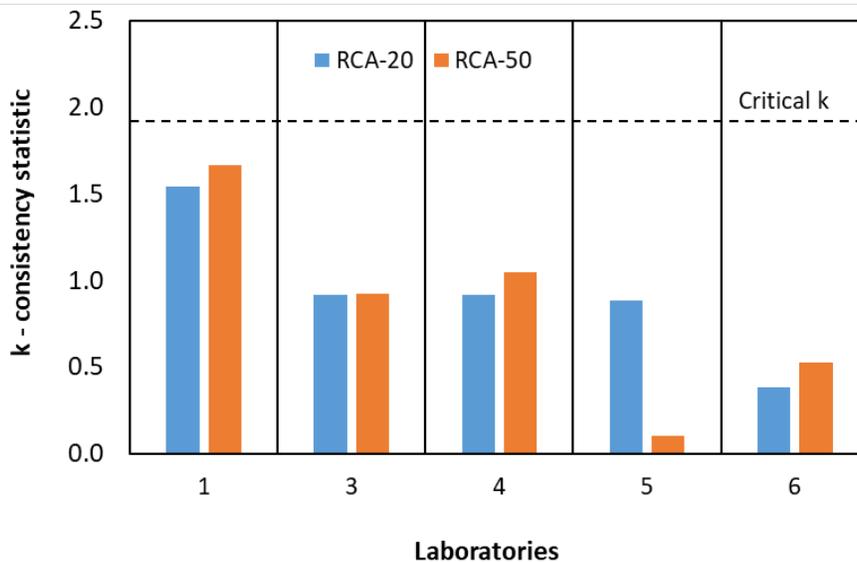


Figure 5.10 Within-laboratory consistency statistics, k, by laboratories

6. CONCLUSIONS

RCA investigation meets the strategic goal of reducing environmental impacts on infrastructure by using a waste material of RCA in new concrete construction. Test results show that using previously damaged concrete with ASR often yields innocuous concrete because the reaction has run its course. The major conclusions of the RCA project are as follows:

- Using RCA from HR aggregate up to 40 percent replacement of coarse aggregates combined with natural NR aggregates can be used in new concrete construction without causing severe ASR damage.
- Within laboratory variability for CPT meets the within-laboratory precision limits. So no recommendation proposed to modify existing ASTM within-laboratory precision limits.
- The results of a seven-laboratory round robin study show the coefficient of variations are within the precision limit defined by concrete prism standard, ASTM C1293.
- Using RCA aggregate, affected with ASR, is less susceptible to ASR than the virgin aggregate when used with a non-reactive aggregate.
- Investigation of autoclaved testing with varying RCA replacement levels found different linear regression trends between the autoclave and CPT test methods.
- Consistency statistic h and k values are within the critical limit for all the laboratory-material combinations. So no further investigation is recommended for any laboratory.

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8. APPENDICES

Appendix A



a) Making frame b) Assembling frames with plywood



c) Installing insulation d) outside view of oven after painting

Figure 8.1 Building process of CPT storage oven

Appendix B

Table 8.1 CPT expansion data for RCA aggregates

Time		Average expansion (%)				
Days	Months	BT-Control	RCA-20	RCA-30	RCA-40	RCA-50
0	0	0.000	0.000	0.000	0.000	0.000
7	0.23	0.002	0.007	0.004	0.004	0.007
28	0.93	0.007	0.014	0.012	0.009	0.010
56	1.87	0.010	0.017	0.022	0.017	0.018
90	3	0.015	0.020	0.025	0.028	0.026
180	6	0.023	0.034	0.039	0.038	0.044
270	9	0.027	0.046	0.052	0.050	0.054
360	12	0.033	0.054	0.060	0.061	0.066

Table 8.2 CPT expansion data for within-laboratory RCA-20 aggregates

Time		Average Expansion (%)						
Days	Months	BT-Control	RCA-20-J1	RCA-20-J2	RCA-20-Z1	RCA-20-Z2	RCA-20-F1	RCA-20-F2
0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.23	0.002	0.007	0.005	0.008	0.007	0.001	0.004
28	0.93	0.007	0.014	0.017	0.015	0.011	0.012	0.014
56	1.87	0.010	0.017	0.026	0.017	0.021	0.019	0.019
90	3	0.015	0.020	0.031	0.024	0.026	0.022	0.025
180	6	0.023	0.034	0.044	0.036	0.037	0.038	0.039
270	9	0.027	0.046	0.055	0.041	0.051	0.050	0.049
360	12	0.033	0.054	0.062	0.046	0.055	0.057	0.051

Table 8.3 CPT expansion data for within-laboratory RCA-50 aggregates

Time		Average Expansion (%)						
Days	Months	BT-Control	RCA-50-J1	RCA-50-J2	RCA-50-Z1	RCA-50-Z2	RCA-50-F1	RCA-50-F2
0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.23	0.002	0.007	0.012	0.012	0.009	0.008	0.005
28	0.93	0.007	0.010	0.018	0.023	0.018	0.021	0.020
56	1.87	0.010	0.018	0.029	0.028	0.030	0.028	0.024
90	3	0.015	0.026	0.034	0.034	0.035	0.033	0.030
180	6	0.023	0.044	0.052	0.048	0.052	0.047	0.051
270	9	0.027	0.054	0.063	0.056	0.062	0.063	0.066
360	12	0.033	0.066	0.073	0.063	0.069	0.071	0.073