Evaluation of Recycled Concrete Aggregate for Usage in Highway and Municipal Concrete Applications

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Abstract

Coarse recycled concrete aggregate (RCA) is produced by crushing concrete which has reached the end of its service life. Depending on its intended application, concrete as a construction material exhibits a wide range in physical and mechanical properties. Partially as a consequence of this, RCA exhibits variability in terms of physical properties which can make it less desirable for usage as coarse aggregate in new concrete infrastructure. However, one characteristic of RCA which is consistent is a higher absorptive capacity when compared with natural aggregate (NA). This higher absorptivity may indicate the potential for RCA to provide some internal curing-like benefits when cast in concrete. Internal curing is the method of entraining water in reservoirs within the concrete such that it is drawn from the reservoirs so as to be beneficial to the cement hydration process. Internal curing in concrete has been found to have many benefits including reducing the negative effects of poor external curing.

In this research, two types of saturated coarse RCA have been used to study the effects of different curing practices on the performance of the concrete. Particular emphasis has been placed on those properties that are critical for concrete pavement design. Two curing regimes are used in order better understand the impact of curing practices on the properties of saturated RCA concretes.

The angularity of the RCA had a pronounced negative effect on the slump values of the different concrete mixtures. The two sources oppositely affected the compressive strength: RCA 1 increased the strength while RCA 2 caused a strength decrease. While the RCA types resulted in opposite compressive strength changes, the stiffness of both RCA concrete materials were found to decrease indicating that the density of the aggregate and consequently concrete had a marked effect on elastic modulus.

Studies of the RCAs' desorption characteristics indicated that the RCA sources tested do not have the properties consistent with internal curing agents according to the definition set by previous researchers focused in the field of internal curing of concrete. However, saturated high absorption RCA appeared to provide some benefit in terms of buffering compressive strength loss under MTO specified curing conditions, suggesting a possible contribution of internal curing from the saturated RCA.

When tested at 28 days, the lower quality RCA 2 exhibited the lowest thermal expansion coefficients; however both RCA mixtures exhibited higher variability of results than the NA control mixture.

These results indicate that some RCA concretes may be well suited for use in some pavement applications. While RCA 1 concrete exhibits a strength increase in comparison with natural aggregate concrete, it exhibits a reduction in elastic modulus with similar thermal expansion coefficients. This could reduce the magnitude of stress concentrations in a pavement exposed to thermal stresses.

These results appear to confirm the findings of a University of Waterloo developed RCA classification framework which identifies RCA 1 as being suitable for use in concrete structures.

Introduction

The use of recycled concrete aggregate (RCA), produced by demolishing and crushing previously cast concrete, as a building material is gaining momentum with Canada's construction industry. RCA use in road construction projects in the Province of Ontario more than doubled between 1991 and 2006, and continues to grow [1]. While Canada is a large and resource-rich country, the population distribution makes it such that the availability of aggregate in high density areas is becoming limited. This results in longer distances between the aggregate supply and the location of the construction project, which increases the transportation costs in terms of both monetary and environmental costs [1]. Additionally, areas of high population density produce a large amount of waste which is discarded into landfills. Demolition wastes have also traditionally been landfilled which further increases the load on these facilities. The use of RCA diverts some of this waste stream away from landfills and into new construction. Since the use of RCA helps to alleviate both of these important environmental issues, it is becoming a more desirable building material.

Internal curing is the practice of casting concrete with reservoirs of water entrained within the concrete mixture. These internal reservoirs become effective during the hydration process of concrete after a portion of the mixing water is consumed in the chemical hydration reaction. This creates what is essentially a moisture gradient which draws the water from the reservoirs into the concrete paste matrix. The presence of this extra water allows for a more complete hydration reaction of the concrete, and helps to alleviate the negative effects of concrete drying by replacing any evaporated water prior to the desiccation of the concrete and the onset of shrinkage cracks. In this second case, the internal curing helps to alleviate the effects of non-ideal curing practices [2]. Internal curing in concrete provides several benefits including: reducing plastic, autogenous, and drying shrinkage (and associated cracking), providing increased hydration in cement-rich mixtures, improving late age compressive strength, and reducing the permeable porosity of concrete by increasing the production of hydration products, including calcium silicate hydrate. Consequently, many of these benefits improve durability in cement-rich concrete mixtures. The interfacial transition zone (ITZ) between the internal curing reservoirs and the concrete mortar is found to improve as compared to the ITZ between natural aggregate and the concrete mortar due to higher availability of water [3].

Internal curing is typically provided by fine materials due to two main considerations. Firstly, aggregates which have high enough absorption to provide sufficient internal curing water are inherently weak due to the presence of voids. Therefore replacement of strong coarse aggregate with lightweight materials can significantly reduce the overall strength of the material. Secondly, in order for internal curing to be effective, it should provide water to the entire cement paste matrix. Since water can disperse only about 2-3 mm in dense concrete, this requires dispersal throughout the entire concrete mixture with small enough spacing between water reservoirs such that the entrained water can reach all parts of the cement paste matrix. This is achieved through the use of fine internal curing reservoirs [4].

In comparison to fine aggregate, a larger proportion of coarse aggregate is required to achieve similar particle spacing. Normally it is poor practice to replace large amounts of coarse aggregate with a weaker material and thus this is generally not considered to be a feasible internal curing strategy. The addition of RCA however, is largely driven by external factors such as including a given amount of recycled material to gain environmental credits. This could therefore result in large proportions of absorptive RCA material being present in concrete. If there is benefit to be gained by using that coarse aggregate in a way which would have internal curing-like effects then this could serve to help maximize the utility of RCA which is normally deemed to be a "lower quality" concrete material.

Aggregate Type

The two recycled aggregate sources that were selected for this study are referred to herein as RCA1 and RCA2. RCA1 was produced through the crushing of non-structural concrete from the Region of Waterloo. The concrete came from demolished transportation structures including curbs, gutters, and sidewalks. In most cases this concrete was demolished because of roadway expansion projects and not because of material failures. It should also be noted that because of its age the material was both high quality and very consistent. RCA2 was produced by crushing concrete which was returned to the ready-mix producer prior to concrete setting. The concrete could have been returned for various reasons including improper mix performance or age issues, but was most commonly "left-over" concrete which remained in the ready mix truck at the conclusion of a concrete pour. This material is typically washed from the concrete trucks into piles which would be crushed when a sufficient amount had accumulated. No attempt at proper curing or consolidation was made for the concrete in these piles. Both RCA sources were graded to satisfy the MTO requirements for concrete coarse aggregate, outlined in OPSS 1002 [5].

Previous research performed at the University of Waterloo produced an RCA classification framework which served to classify different RCAs according to their best potential use or application. These applications ranged from use in reinforced structural concrete to use only as a fill material. The framework was developed such that classification depended on aggregate tests. This allows for classification to be performed without knowledge of RCA's source concrete, since this information is often unknown for a given RCA. The framework developed is an excellent step towards the development of a widely source-inclusive tool which could be used industry-wide to achieve much more effective use of existing and future RCAs [6] [7].

According to the classification framework, RCA1 was classified as Class A2 (or Class A1), and RCA2 was classified as C. This implies that RCA1 is "high quality" material and would be suitable for use in structural and non-structural concrete applications. Conversely, RCA2 would be considered "low-grade" material and would be suitable only for use in structural and non-structural fill applications. Thus, the two aggregate types represent two extremes of the RCA quality spectrum. They have both been included in this research to gauge any relative internal curing effects and benefits between a low-grade material, with high absorption capacity (RCA2) and a high-quality material, with lower absorption capacity (RCA1).

Concrete Mixture Proportions

The concrete mixture design used in this research was derived from a mixture design previously developed for RCA research at the University of Waterloo. The designs were developed based on a direct volumetric replacement basis. The direct replacement involves replacing natural aggregate with equal volumes of RCA such that the overall volume of the concrete produced stays constant. This method is also referred to as the Absolute Volume method. The proportions used for the batching of concrete are summarized in Table 1.

The mixtures have been standardized to have a water content corresponding to a 0.370 water cement (w/c) ratio plus full saturation of aggregate. This water is included in each mixture in combinations of three phases: entrained in and adhering to coarse aggregate, and as mixing water.

Curing Conditions

Two different curing regimes were compared in this study. The first included sample storage at 100% relative humidity (RH) at 24°C up until the time of testing. This was designated as Moist Curing and was considered to be "ideal". The second curing regime was in accordance with MTO OPSS 350 and a modified CSA A23.2-3C [8]. This included 7 days moist burlap curing covered by a vapour barrier. After the seven days, the samples were exposed to drying in the conditions present within the lab which were approximately 50% ± 10% RH and a temperature of 21 ± 2°C. The temperature within the lab was similar to the moist curing room and was maintained at a relatively constant level. This second curing regime was designated as Specified Curing (spec-curing). The beneficial effects of internally entrained water were theorized to be more apparent in situations where external curing water is not as readily available, such as in the case of spec-curing. This also would more closely resemble field conditions in most applications.

Aggregate Replacement Level

Previous research at the University of Waterloo indicated that replacing natural aggregate with RCA had little observable effect on compressive or flexural strength up to a 30% replacement threshold [9]. This conclusion was based on the results of testing mixtures including only one source of RCA. In order to gauge whether similar results are found when varying qualities of RCA are used, a 30% aggregate replacement mixture is included within this study.

The 30% aggregate replacement is performed on the basis of volumetric proportioning using the natural aggregate as a reference point. For each RCA source, the 30% replacement amount is calculated based on the dry density of the RCA.

Concrete Naming Convention

The concrete sample sets were differentiated based on the aggregate type, curing regime, coarse aggregate saturation level (part of a separate study), and RCA replacement level. A naming convention for the different concrete types was adopted in order to identify these variables. Figure 1 shows the naming convention which was adopted and used.

$\boxed{\text{RCA1}}\ \boxed{\text{S}}\ \boxed{\text{100}}\text{-}\boxed{\text{30}}$

(a) (b) (c) (d)

Figure 1: Concrete naming convention

The name for each concrete type had four distinct components which are labelled a) through d). Component a) indicates the coarse aggregate type in the mixture. This could be NA (for natural aggregate), RCA1, or RCA2. Mixtures with both NA and an RCA type were named based on the RCA type. Component b) refers to the curing regime which the samples were subjected to. In this case, "S" indicates the specified curing regime and "M" represents moist curing. Component c) indicates the target saturation level of the coarse aggregate at the time of batching, which in this study is always 100%. Finally, component d) refers to the proportion of the original NA which was replaced volumetrically by RCA. The replacement levels were 0% (for control mixtures), 30% (for "acceptable level" mixtures), and 100%.

Desorption of Coarse Aggregate

The desorption of a material refers to the manner in which it releases entrained water into the surrounding environment. In this study it refers to the amount of entrained moisture within an aggregate which is released in an environment with a controlled RH.

The feasibility of a material as an internal curing agent is often considered in reference to the material's desorption characteristics. Previous research, specifically focused on fine lightweight aggregate, found that a significant proportion of the moisture contained within the aggregate should be released at a high RH (approximately 93%) in order to provide the most benefit to the hydration process [10]. While this previous research and most internal curing applications focus on fine materials for both surface area and dispersion benefits, this threshold RH is considered to be relevant when considering the desorption of a coarse material.

For the purpose of this research, the isotherms which represent the desorption behaviours of the materials being used were developed based on Section 7.4 of ASTM C1498 [11]. This method is a simple evaluation technique which provides insight into the feasibility of a material in terms of internal curing potential.

Using saturated salt solutions, five specific RH environments were created. A summary of the saturated salt solutions and the RH environments are presented in Table 2. The production of saturated salt solutions was completed in accordance with ASTM E104-02 [12]. The environments were created using air-tight containers which were housed in a cabinet intended to maintain the temperature and RH of each environment.

Initially saturated samples of each coarse aggregate type were placed into each of these environments sequentially from high to low RH. This allowed for controlled release of moisture from the aggregate in order to produce the desorption isotherm. Mass losses (due to water loss) were recorded every 24 hours and aggregate samples were progressed to the next environment when they had maintained a constant mass (within 0.1% of the specimen mass) for three consecutive days.

Compressive Strength

Compressive strength is an important material property of concrete and is often related to the quality of the concrete. Compressive strength is commonly used in material specification as it can be easily tested and correlated to other properties of concrete. Compressive strength of each sample was performed in accordance with CSA A23.2-9C [8].

Those specimens which were moist cured prior to testing were maintained in this moisture condition until testing was performed. Three specimens were tested at each condition and the average of the three results was used.

Splitting Tensile Strength

Splitting tensile strength testing is a straight-forward method for determining concrete strength in tension. It is performed by applying a distributed load along the edges of a cylinder which are diametrically opposite of one another. This produces a near-uniform tensile stress along three quarters of the vertical plane bounded on the top and bottom by the uniform compression loads.

During the concrete hydration process, microcracks form in the ITZ between the aggregate and mortar due to mechanical property differences between the two materials and to shrinkage or thermal stresses. These microcracks are believed to be the points where stress concentrations develop under tensile loading which eventually lead to material failure. Because of this, splitting tensile strength depends largely on the ITZ, which has been theorized to be weak in RCA concretes. The splitting tensile strength of concrete samples was tested in accordance with the procedures outlined in CSA A23.2-13C [8].

Static Modulus of Elasticity

Elastic properties of materials are used by engineers in order to gauge the strain response in a material at a given stress level. Although concrete's stress strain behaviour is non-linear and non-elastic, it is typically assumed that concrete behaves linearly under low, service loading [13]. This portion of linearity is described by the Modulus of Elasticity which approximately represents the slope of linear portion on concrete's stress-strain plot.

When the stress-strain relationships for aggregate and cement paste are examined, it can be seen that both behave approximately linearly. Cement paste exhibits low stiffness as compared to aggregate, and concrete exhibits a stiffness between the two. As the stress levels applied to the concrete increase the progressive microcracking at the ITZ between concrete's two phases is what causes the non-linear behaviour of concrete. As microcracks develop, local stress concentrations develop which are higher than the nominal stress on the material. This results in increased strain in the non-linear portions of the concrete stress-strain relationship. Concrete produced using natural aggregate is assumed to have an elastic modulus between 21 – 42 GPa [13].

The ITZ of RCA concrete is typically assumed to be of poorer quality than in natural aggregate concrete and therefore the strains in the RCA concrete develop at lower stresses resulting in a lower elastic modulus. The stiffness of RCA itself is also typically lower than natural aggregate. Previous studies have found that 100% replacement of natural aggregate with RCA in concrete results in an elastic modulus reduction of approximately 20-30%, although some studies have found the elastic modulus as low as 50%. While it is acknowledged that ITZ quality plays a role in elastic modulus, it is unclear whether methods used to improve the ITZ including varying presaturation levels [14, 15] or mixing procedures [16]cause large effects in the static modulus of RCA concrete. Curing conditions have been found to have some small effect on the relative decrease in elastic modulus of concrete, but largely due to a decrease in the modulus of the control concrete's elastic modulus [17]. The static modulus of elasticity (MOE) was performed in accordance with the procedure outlined in ASTM C469/C469M−10.

Linear Coefficient of Thermal Expansion

The Coefficient of Thermal Expansion (CTE) is a material property which quantifies the expected change per unit length in a linear dimension caused by changes in the material's temperature, with units of (10^{-6} mm/mm)/°C or (x10^{-6}/°C). In concrete, CTE is the net effect of two processes. These processes include the typical expansion of solids and the expansion related to the movement of water in the capillaries and gel pores of the concrete.

The CTE of concrete is an important characteristic in design of concrete structures. This is especially true when considering a structure which will be subjected to a wide range of temperatures throughout the design life. One such type of structure is found in rigid pavements in northern climates. The large temperature range to which an exposed Canadian concrete pavement is exposed can cause significant thermally-induced length changes. These can result in induced stresses where these length changes are externally restrained. Since these stresses can result in premature pavement failures, the response of concrete to thermal loading is an important consideration.

Concrete is a composite material and its constituent materials have different thermal properties. The thermal behaviour of the solid component of concrete is governed overall by the proportions within the mixture.

Since aggregate generally comprises the largest proportion of concrete, the thermal properties of the aggregate significantly influence the behaviour of the concrete. Natural aggregate typically has CTE values which range from approximately 4 x 10^{-6}/°C for limestone to 12 x 10^{-6}/°C for quartzite [2]. Because CTE testing is more easily performed on a sample with easily measured dimensions, CTE testing is generally performed on cylindrical rock cores instead of crushed aggregate of the same material. This testing method is not available for RCAs unless cores were taken of the previous concrete structure, which is rarely the case. Similar to concrete, the CTE values of RCA will greatly depend on the aggregate type used. Since RCAs generally have a higher absorption capacity than natural aggregates, they theoretically should be more prone to the water-related effects of temperature changes.

A smaller proportion of concrete volume is made up of cement paste which generally has a higher CTE (typically 9 – 22 x10^{-6}/°C) [13]. It is also the area where most of the water is situated within concrete and is therefore more susceptible to the swelling pressures associated with water. The swelling is due to the decrease in capillary meniscus tension with an increase in temperature [2]. Capillary meniscus tension is the surficial force exerted by the surface of water on the concrete structure which surrounds it. As temperatures increase, this force is reduced, resulting in overall swelling. This also allows for the flow of water from capillaries into the smaller gel pores which also causes swelling.

The focus of this study is to evaluate RCA as a construction material so the CTE testing procedure was developed to test in conditions similar to what may be reasonably expected in the field. This involved the following considerations:

- Samples would be tested according to a modified version of ASTM C531 similar to previous research performed at the University of Waterloo to allow for some comparison of results
- Samples were to be allowed to equilibrate for 24 hours in the concrete lab which was considered to have an RH of 50% ± 10% and a temperature of 21 ± 2°C
- Testing would consider the length changes occurring between temperatures of approximately 20°C and -15°C
- Values obtained would be compiled and considered as an average CTE

The linear coefficient of thermal expansion (LCTE) of the concrete was measured according to a modified procedure similar to that outlined in ASTM C531 [19]. Samples were initially marked to show vertical lines indicating diametrically opposite sides of the samples. Using a cold temperature epoxy, aluminum strain points were attached to the samples along these vertical lines, with two points on each side of each specimen. The strain points were placed using a 100 mm spacer to ensure that each reading had the same gauge length. Samples were exposed to the environment within the concrete lab (RH: 50% ± 10%, Temp: 21 ± 2°C) for 48 hours prior to the beginning of testing to allow the exposed surfaces to equilibrate to the environmental conditions. The epoxy was allowed to harden during the equilibration phase of the concrete.

Using a digital laser thermometer, the surface temperature of each specimen was measured and recorded at the time of testing. A digital strain gauge was then used to measure the spacing between each set of strain points; this gauge was capable of measuring with accuracy to 0.001 mm. After all specimens had been measured, they were placed in an insulated cooler which was placed open in a freezer with a temperature of approximately -15°C for a period of 24 hours. After this period the coolers were closed and then removed from the freezer. Samples were removed from the coolers individually and the temperatures and strains were measured and recorded again. The samples were then exposed to the lab environment again for 24 hours before re-measuring. This cycle was repeated for two freezing cycles.

This method varies from traditional CTE testing as it considers the low-temperature behaviour of concrete, which is of interest for Canadian pavements.

Statistical Evaluation

The results of each test were evaluated to gauge their statistical significance. This evaluation was performed by calculating the least significant difference (LSD). This value represents the smallest difference between two mean values which can be considered statistically significant at 95% confidence. The LSD was calculated in each case using analysis of variance (ANOVA) and modified Bonferroni t-test. This evaluation method considers variations in a single factor and therefore a separate LSD value was calculated for each complement of samples for a given variation.

Error bars in some graphical representations represent standard deviations of the measured results to indicate the level of variation.

Results

Desorption of Coarse Aggregate

The results of the desorption testing are illustrated in Figure 2. Each aggregate type exhibited different desorption behaviour as can be seen in the three isotherms. The desorption behaviour of natural aggregate is shown for reference. At each RH level, the error bars shown represent one standard deviation in either direction.

The isotherms displayed are in terms of percentage of total retained moisture not the amount of retained moisture. Due to the differences in overall absorption capacity 100% retained water indicates the highest total water level in RCA2, then RCA1, and the lowest in NA. The vertical red dashed line on the plot indicates the 93% RH threshold which is considered to be the approximate level at which internally entrained water should desorb in order to provide benefits to the hydration process.

Both RCAs retained most of their entrained moisture in the 98% RH environments and 90% or more of their entrained moisture in the 85% RH environment. Very little moisture was found to be drawn out at the 93% RH level. This indicates that the materials do not desorb enough of their water to be desirable for internal curing applications. The relatively small error bars in the high RH readings indicate that the results found are generally repeatable and reliable. At lower RH levels, the variation within the results increases, but these RH levels do not largely impact the internal curing suitability of the materials.

A considerable amount of desorption occurs in RCA1 and RCA2 between RH levels of 85% and 70% with losses of 40% and 25% of their respective entrained moisture. Below the 70% RH level, it appears that the material tends to retain the entrained moisture. At the 33% RH level both still retain approximately 40% and 50% of their initially entrained water respectively. These results suggest that the RCAs of this study do not perform as typical internal curing agents as they retain the bulk of their entrained moisture past the point where more water would be considered most helpful to the hydration process.

It is possible that the saturated aggregates within concrete could help to alleviate the effects of moisture gradients within curing concrete that result in stress gradients [20]. As the internal RH level of concrete drops to ambient levels, the exposed surfaces of the concrete drop first, which results in a moisture gradient. As the concrete dries, the internal pore fluid pressure drops thereby initializing drying shrinkage. Since the pore fluid pressure drops on the outside of the concrete faster than the inside, stress gradients are formed due to differential shrinkage. Since the water entrained in the RCA appears to largely remain in the aggregate at RH levels of 93%, it may be available at later stages of hydration. When external drying reduces the internal RH of concrete to the 70% level, the RCA may be able to desorb a more substantial amount of its entrained water. This largely depends on the pore structure of the concrete at this point in time and whether water could flow out of the RCA. Retaining a less severe initial moisture gradient within the concrete could allow the concrete to develop more strength to resist the onset of shrinkage cracking.

Compressive Strength (Curing Comparison)

Figure 3 illustrates the compressive strength development for the mixtures used within the curing comparison. Table 3 tabulates the statistical analysis of the different curing regimes based on a 5% LSD. In all cases the moist-cured samples exhibited compressive strength that was similar to but higher than the MTO specified curing (spec-cured) samples at the age of 7 days. This indicates that the burlap-curing portion of spec-curing provides comparable benefit to 100% RH conditions for these mixtures.

After 7 days, the three concrete types developed compressive strength in three distinct ways. The NA mixtures maintained a disparity between the compressive strength of moist and spec-cured mixtures of approximately 4 MPa until 28 days age, which was not statistically significant. After this point, the moist-cured mixture continued to develop strength at a similar rate while the spec-cured mixture's strength gain was retarded. This resulted in a significant difference in strength at 91 days.

The moist-cured and spec-cured RCA1 mixtures also gained strength approximately equally up until the 28 day test. At this point the strength gain of the spec-cured mixture reached a plateau while the moist-cured specimen continued to gain strength. A similar plateau was reached at 56 days for the moist cured samples and by the 91 day test, the difference between the compressive strength of the two curing regimes was still statistically insignificant. The compressive strength results for the RCA1 samples had relatively high standard deviations which resulted in high LSD values which affect the insignificant different between the "M" samples and the "S" samples. Even though the LSD is larger, the difference between the means of the compressive strength for the "M" and "S" samples is small in comparison to the differences observed in the mixtures containing the other aggregate types.

The compressive strength of the RCA2 mixtures remained approximately at parity until the 56 day test at which point the spec-cured samples' strength gain plateaued and the moist cured samples continued to gain strength. At 91 days, the differences in compressive strength between moist cured and spec-cured RCA2 mixtures were statistically significant at 95% confidence.

The entrained moisture in both RCA mixtures had different compressive strength gain benefits under spec-curing conditions. RCA2 extended the period of initial strength gain while RCA 1 improved the later age strength of the mixtures. These benefits coincide with the previous finding that RCA1 concretes retain moisture in exposed conditions for longer periods than RCA2 and therefore exhibit benefits at later ages.

Relatively, the entrained moisture of RCA2 appeared to make it perform similarly to the NA mixture under spec-curing conditions, despite considerable variation between NA and RCA2 concretes observed when both are cured in ideal conditions. RCA1 mixtures exposed to spec-curing behaved similarly to moist-cured NA concrete. Figure 4 illustrates the compressive strength of the spec-cured mixtures relative to their moist cured counterparts.

Except for one slight increase, all compressive strengths were observed to be lower in those mixtures which were exposed to the spec-curing regime. This is intuitive as moist-curing provides a continuous source of curing moisture in addition to any entrained moisture.

At every age, the performance of spec-cured RCA mixtures performed relatively better than the NA mixtures in terms of compressive strength. This improvement is observed specifically at ages of 7 to 28 days. At later ages, the benefit relative to the NA mixtures is less pronounced, but still observable. RCA2 exhibits this relative benefit up to 56 days age. An explanation for this improvement is that the entrained water within the aggregate provided a buffer for the concrete from the detrimental effects of spec-curing in comparison to moist curing. It was previously found that the aggregate would not perform as a traditional internal curing agent due to unfavourable desorption behaviour, however the entrained moisture could still provide some moisture to alleviate the negative effects of drying past the point of initial hydration.

Splitting Tensile Strength (Curing Comparison)

Figure 5 exhibits the splitting tensile strengths measured for the mixtures being compared at ages of 28 and 91 days. None of the differences in tensile strength due to differences in curing regime were found to be statistically significant.

The curing conditions appear to have the greatest effect on the NA mixtures. Under the spec-curing conditions, the NA mixture exhibits an average drop of 17% in tensile strength. The spec-cured NA samples behaved similarly to the RCA samples exposed to either curing regime.

The RCA mixtures did not exhibit a similar drop in tensile strength with spec-curing, but this should not necessarily be attributed to any benefit of entrained moisture as 0% saturation RCA mixtures exhibited similar tensile strengths.

It appears as though the magnitude of tensile strength loss associated with spec-curing NA concrete is similar to that of RCA use. These losses do not appear to be cumulative as spec-cured RCA mixtures are not appreciably lower than moist-cured RCA mixtures.

Compressive Strength (30% Replacement)

Figure 6 illustrates the compressive strength development for the 30% RCA replacement mixtures and the corresponding NA mixture. Table 5 summarizes the statistical evaluation of the compressive strength for 30% replacement at 28 and 91 days.

Under MTO-specified curing conditions replacing 30% of the NA in a given concrete with RCA of good or poor quality results in only minor variations in compressive strength. At 28 days both of the 100% saturated RCA mixtures had significantly higher compressive strength than the corresponding NA mixture. At 91 days, the only 30% replacement mixture which was significantly different than the NA mixtures was the fully saturated RCA1. This mixture exhibited compressive strength higher than its corresponding NA mixture. These findings are similar to those previously discussed, which were that fully saturated RCA1 produced higher overall compressive strengths while fully saturated RCA2 provided early age strength gain benefits.

Figure 7 illustrates the compressive strength of the 30% RCA mixtures relative to the compressive strength of the corresponding saturation NA mixtures. The horizontal line on the plot represents the line of equivalency between the two mixtures. This figure shows the effects of a 30% RCA replacement on the compressive strength of concrete. At all ages, the strength of RCA1 and RCA2 mixtures are higher than or approximately equal to the NA mixtures. This appears to indicate that the compressive strength of concrete is not unduly compromised by adding 30% RCA under these conditions.

Splitting Tensile Strength (30% Replacement)

Table 6 summarizes the statistical evaluation of the tensile strengths for the 30% replacement mixtures at 28 and 91 days. The effects of RCA replacement on tensile strength are more severe and less predictable than the effects on compressive strength. This variation can be seen in the wide range of the coefficients of variation, which are not consistently high for a given aggregate type. Generally the tensile strengths of the 30% replacement mixtures were less than those of the NA mixtures. The magnitude of this reduction varied, with a maximum reduction of 12%. Based on the test results however, none of the changes in tensile strength are statistically significant at 95% confidence. These indicate that the splitting tensile test produces results that vary significantly.

Modulus of Elasticity (30% Replacement)

Figure 8 shows the elastic modulus of the various 30% replacement mixtures relative to those of the NA mixtures with similar coarse aggregate saturations. The horizontal line at the top of the plot indicates equivalency between the results being compared. Table 7 summarizes the statistical evaluation of the 30% replacement mixtures at 28 and 91 days.

None of the 30% RCA mixtures exhibited elastic moduli as high as their corresponding control NA mixtures. Each result exhibited a decrease in elastic modulus of between about 2% and 15%.

The 30% RCA replacement concretes displayed a drop in relative stiffness over the period between 28 and 91 days. The control concrete experienced a 33% increase in elastic modulus over this time period while the replacement mixtures experienced smaller increases. All concretes experienced increases in elastic modulus during this time period; however the control mixture showed the largest increase. The three aggregate types are not statistically different at either age, indicating that with saturated RCA, a 30% replacement does not significantly affect the stiffness of the concrete.

Linear Coefficient of Thermal Expansion (30% Replacement)

Figure 9 shows the results of the thermal expansion testing at 28 days. The error bars shown on each result indicate one standard deviation in either direction in order to illustrate the variability of the results.

At the initial testing at the age of 28 days, the replacement of 30% RCA lowers the thermal expansion of the concrete at low temperatures. Based on the gathered data, the thermal expansions of both RCA mixtures were significantly lower than those of the NA mixture at 95% confidence. This appears to indicate that the inclusion of 30% RCA has a beneficial effect on the thermal expansion of concrete at low temperatures, regardless of RCA quality.

CONCLUSIONS

Curing Comparison

The entrained moisture in both RCA mixtures had different compressive strength gain benefits under spec-curing conditions. RCA2 extended the period of initial strength gain while RCA 1 improved the later age strength of the mixtures. These benefits coincide with the previously discussed findings that RCA1 retains moisture for longer time periods than RCA2. The NA samples exposed to spec-curing conditions exhibited lower compressive strength than their corresponding moist-cured samples and the difference in strength between the samples of the two curing regimes continued to grow until the end of testing. The benefits observed in the concretes produced with either RCA type were not observed in the NA samples. This indicates that concretes produced with saturated RCA have benefits in concrete applications with the potential for air drying after short periods of curing. This increases the value of RCA as a material for use in concrete production.

Spec-curing affects the tensile strength of NA mixtures, but did not affect 100% saturated RCA mixtures significantly. The tensile strength of RCA mixtures under both curing conditions were statistically the same and were similar to the tensile strength of spec-cured NA samples. This indicates that concrete applications which typically undergo spec-curing would not have significantly worse tensile strength properties with 100% replacement of NA with saturated RCA. This is significant because tensile strength loss is often considered to be a problem associated with RCA concrete.

Acceptable RCA Level Comparison

The compressive strength of concrete is not unduly compromised by adding 30% RCA under the conditions studied. The addition of poor quality RCA2 under the spec-curing conditions resulted in no significant loss in 91 day compressive strength. At 28 days, both RCA concretes had significantly higher compressive strength than the control NA mixture and at 91 days, the only statistically significant mixture was the 30% RCA1 which had higher strength than either of the NA or RCA2 concrete mixtures. Fully saturated RCA1 produced higher overall compressive strengths while fully saturated RCA2 provided early age strength gain benefits. These results indicate that concretes with 30% RCA which is fully saturated are not only statistically similar at late ages, but provide early age benefits over NA concretes in terms of compressive strength gain. This indicates some significant value of RCA in some concrete applications which require quick concrete strength gains.

30% RCA inclusion resulted in tensile strength reductions of up to 12% in comparison to NA mixtures, though some increases due to 30% RCA inclusion in mixtures were observed. None of these changes were statistically significant. Concrete applications which require high tensile strengths do not preclude the use of 30% RCA concretes as tensile strength was not significantly affected by either RCA type.

30% RCA inclusion resulted in reductions in elastic modulus of between about 2% and 15%. The saturated RCA mixtures were not statistically distinct from the NA mixture at either testing age. While not statistically significant, MOEs for 30% RCA concretes were consistently lower than the NA concretes. At 28 days, the inclusion of 30% RCA of either type or saturation level into the mixtures had a significant beneficial effect on the thermal expansion properties of concrete. This could add considerable value to RCA in terms of concrete use. Low thermal expansion in concrete could be very useful in applications such as concrete pavements which are subjected to significant temperature changes. These changes can result in high stresses when conventional restrained concrete pavements expand or retract. The magnitude and the damage caused by these stresses could be reduced by low LCTE RCA concrete.

References

[1] Ministry of Natural Resources, "State of the Aggregate Resource in Ontario Study," February 2010. [Online]. Available: http://www.mnr.gov.on.ca/stdprodconsume/groups/lr/@mnr/@aggregates/documents/document/286996.pdf. [Accessed May 2013].

[2] R. Henkensiefken, D. Bentz, T. Nantung and J. Weiss, "Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions," *Cement & Concrete Composites,* p. 427–437, 2009.

[3] D. P. Bentz and W. J. Weiss, "Internal Curing: A 2010 State-of-the-Art Review," U.S. Department of Commerce: National Institute of Standards and Technology, 2011.

[4] D. P. Bentz, P. Lura and J. W. Roberts, "Mixture Proportioning for Internal Curing," *Concrete International,* pp. 35-40, February 2005.

[5] Ontario Provincial Standards (OPS), OPSS.PROV 1002: MATERIAL SPECIFICATION FOR AGGREGATES - CONCRETE, 2013.

[6] L. Butler, S. Tighe and J. West, "Guidelines for the Selection and Use of Recycled Concrete Aggregates in Structural Concrete," *Transportation Research Record: Journal of the Transportation Research Board, Vol 2335,* pp. pp 3-12, 2013.

[7] L. Butler, J. West and S. Tighe, "Effect of Recycled Concrete Coarse Aggregate for Multiple Sources on the Hardened Properties of Concrete with Equivalent Compressive Strength," *Journal of Construction and Building Materials, Vol. 47,* pp. pp 1292-1301, 2013.

[8] CSA, "Concrete materials and methods of concrete construction/Test methods and standard practices for concrete," Canadian Standards Association, Mississauga, ON, 2009.

[9] J. T. Smith and S. Tighe, "Recycled Concrete Aggregate – A Viable Aggregate Source For Concrete Pavements," University of Waterloo, 2009.

[10] J. Castro, L. Keiser, M. Golias and J. Weiss, "Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures," *Cement & Concrete Composites 33 ,* pp. 1001-1008, 2011.

[11] American Society for Testing and Materials (ASTM), "C1498: Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials," ASTM International, West Conshohocken, PA, USA, 2010.

[12] American Society for Testing and Materials (ASTM), "E104: Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions," ASTM International, West Conshohocken, PA, USA, 2007.

[13] J. F. Lamond and J. H. Pielert, STP169D: Significance of Tests and Properties of Concrete and Concrete-Making Materials, West Conshohocken, PA, USA: ASTM International, 2006, pp. 226-237.

[14] C. S. Poon, Z. H. Shui, L. Lam, H. Fok and S. C. Kou, "Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete," vol. 2004, no. 34, pp. 31-36, 2004.

[15] L. Ferreira, J. de Brito and M. Barra, "Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties," *Magazine of Concrete Research,* vol. 63, no. 8, 2011.

[16] V. W. Tam and C. Tam, "Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc," *Construction and Building Materials 22,* p. 2068–2077, 2008.

[17] N. Fonseca, J. de Brito and L. Evangelista, "The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste," vol. 2011, no. 33, 2011.

[18] A. M. Neville, Properties of Concrete, New York: John Wiley & Sons, Inc., 1997.

[19] American Society for Testing and Materials (ASTM), "C531: Standard Test Method for Linear Shrinkage and

Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes," ASTM International, West Conshohocken, PA, USA, 2012.

[20] Z. C. Grasley, D. A. Lange and M. D. D'Ambrosia, "Internal relative humidity and drying stress gradients in concrete," *Materials and Structures, 39,* pp. 901-909, 2006.

Table 1: Concrete Mixture Proportions

Water (kg/m^3)*	180
Cement (kg/m^3)	487
Coarse NA (kg/m^3)**	1094
Coarse RCA1 (kg/m^3)**	972
Coarse RCA2 (kg/m^3)**	939
Volume of Coarse Aggregate (m^3/m^3 concrete)	0.412
Fine Agg. (kg/m^3)	625
Water-Cement Ratio	0.370

*water content does not include extra water added to account for aggregate absorption

**coarse aggregate values represent proportion for 100% of given aggregate type. 30% mixtures included 30% of RCA mass and 70% of NA mass

Table 2: Aqueous Salt Solutions and Associated Equilibrium RH

Saturated Aqueous Salt Solution	Equilibrium RH (at 20° C)
Potassium Sulphate	97.6 ± 0.6%
Potassium Chloride	85.1 ± 0.3%
Sodium Chloride	75.5 ± 0.2%
Potassium Iodide	69.9 ± 0.3%
Magnesium Chloride	33.1 ± 0.2%

Table 3: Statistical comparison of compressive strength at 28 and 91 days (curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean Comp. Strength (MPa) (28 day)	48.7	44.9	55.1	54.5	45.3	45.1
STD DEV (MPa)	2.1	0.1	5.0	3.2	1.4	0.6
COV (%)	4.4	0.3	9.0	6.0	3.1	1.3
LSD (MPa)	**5.3**		**14.7**		**3.8**	
Mean Comp. Strength (MPa) (91 day)	61.6	51.2	62.8	58.0	52.8	46.9
STD DEV (MPa)	0.0	0.6	0.3	5.7	0.7	0.8
COV (%)	0.0	1.1	0.5	9.8	1.3	1.7
LSD (MPa)	**1.4**		**14.1**		**2.6**	

Table 4: Statistical comparison of tensile strength at 28 and 91 days (curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean Tens Strength (MPa) (28 day)	4.6	4.1	3.6	3.7	3.5	3.0
STD DEV (MPa)	0.4	0.5	0.2	0.5	0.3	0.2
COV (%)	11.8	4.8	13.5	10.0	5.5	7.4
LSD (MPa)	**1.6**		**1.3**		**1.0**	
Mean Tens Strength (MPa)(91 day)	4.9	3.6	3.7	3.7	3.5	3.8
STD DEV (MPa)	0.3	0.6	0.1	0.2	0.2	0.4
COV (%)	16.8	4.7	6.6	11.1	11.1	5.5
LSD (MPa)	**1.7**		**0.7**		**1.2**	

Table 5: Statistical comparison of compressive strength at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30
Mean Comp. Strength (MPa) (28 day)	44.9	47.2	48.7
STD DEV (MPa)	0.1	0.4	0.3
COV (%)	0.3	0.9	0.6
LSD (MPa)	**1.1**		
Mean Comp. Strength (MPa) (91 day)	51.2	57.4	51.2
STD DEV (MPa)	0.6	0.6	0.5
COV (%)	1.1	1.0	0.9
LSD (MPa)	**2.0**		

Table 6: Statistical comparison of tensile strength at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30
Mean Tens. Strength (MPa) (28 day)	4.1	3.9	3.6
STD DEV (MPa)	0.5	0.3	0.2
COV (%)	11.8	7.4	5.6
LSD (MPa)	**1.3**		
Mean Tens. Strength (MPa) (91 day)	3.6	4.3	3.5
STD DEV (MPa)	0.6	0.2	0.4
COV (%)	16.8	5.5	10.2
LSD (MPa)	**1.7**		

Table 7: Statistical comparison of elastic modulus at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30
Mean MOE (MPa) (28 day)	36707	35513	36176
STD DEV (MPa)	3082	870	1155
COV (%)	8.4	2.4	3.2
LSD (MPa)	**7593**		
Mean MOE (MPa) (91 day)	42820	40270	36829
STD DEV (MPa)	2705	668	524
COV (%)	6.3	1.7	1.4
LSD (MPa)	**6187**		

Table 8: Statistical comparison of LCTE values at 28 and 150 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30
Mean LCTE ($x10^{-6}$/°C) (28 day)	11.1	7.5	8.0
STD DEV($x10^{-6}$/°C)	1.0	2.0	2.4
COV (%)	9.3%	26.5%	29.3%
LSD ($x10^{-6}$/°C)	**2.2**		
Mean LCTE ($x10^{-6}$/°C) (150 day)	7.0	16.7	5.2
STD DEV($x10^{-6}$/°C)	2.5	3.5	2.4
COV (%)	35.1%	20.8%	46.5%
LSD ($x10^{-6}$/°C)	**3.4**		

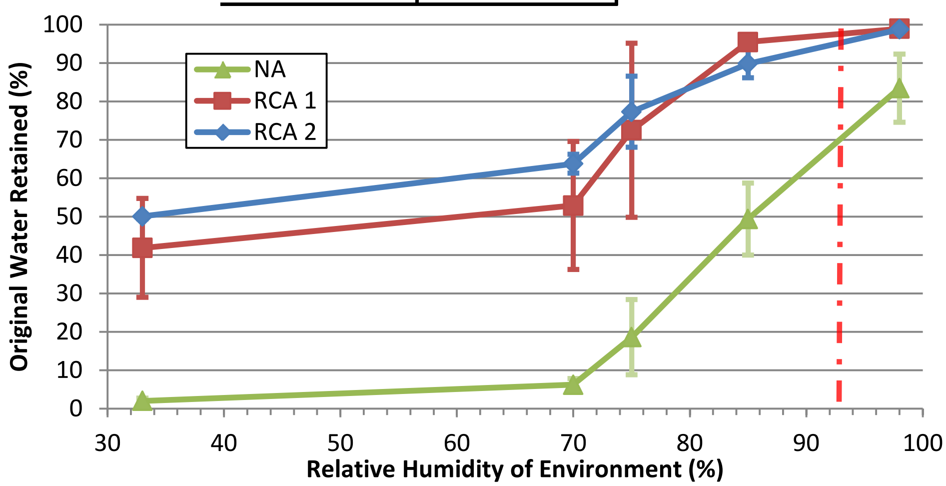

Figure 2: Desorption isotherms for coarse aggregates

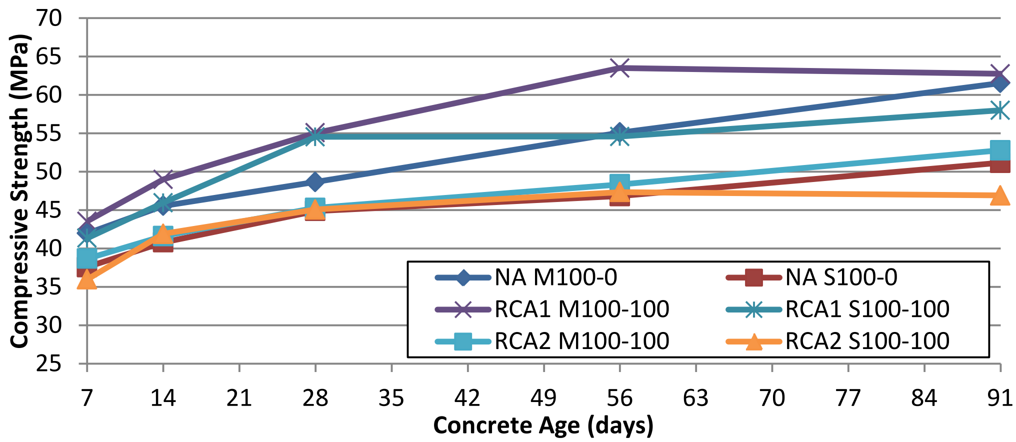

Figure 3: Compressive strength development for curing comparison

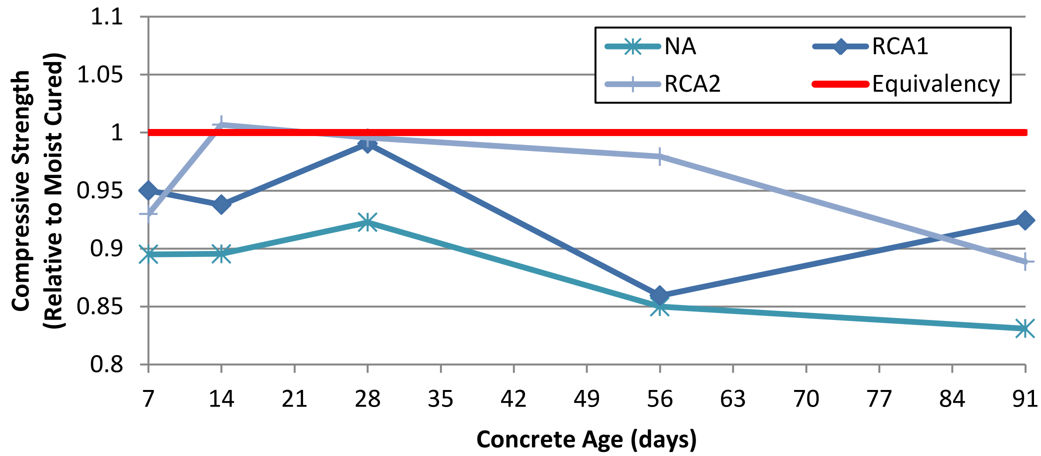

Figure 4: Compressive strength of spec-cured mixtures relative to moist-cured mixtures

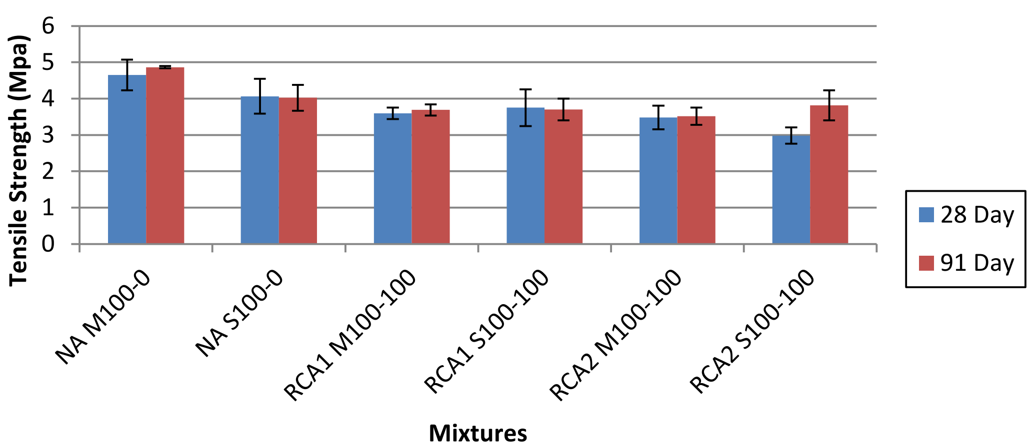

Figure 5: Tensile strength development for curing comparison

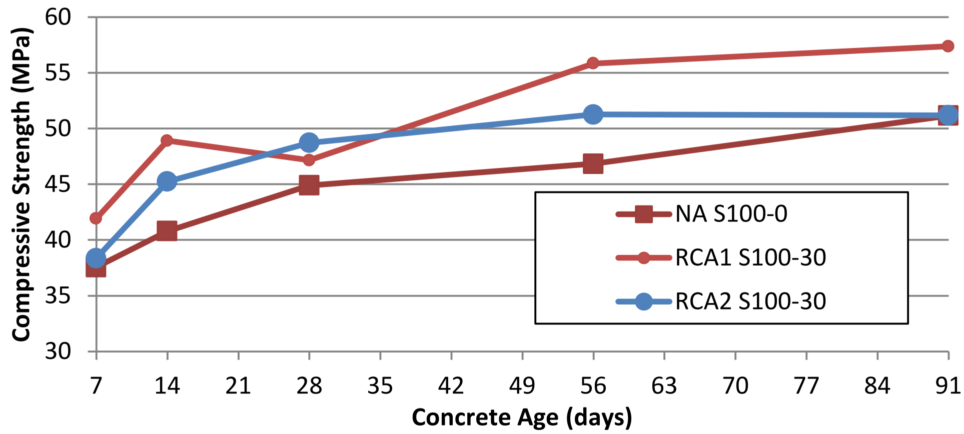

Figure 6: Compressive strength development for acceptable replacement level comparison

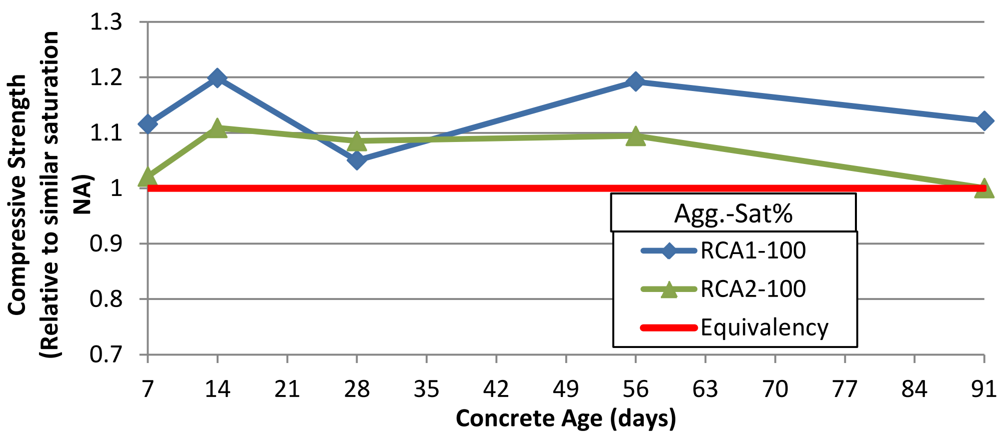

Figure 7: Compressive strength of 30% RCA mixtures relative to NA mixtures

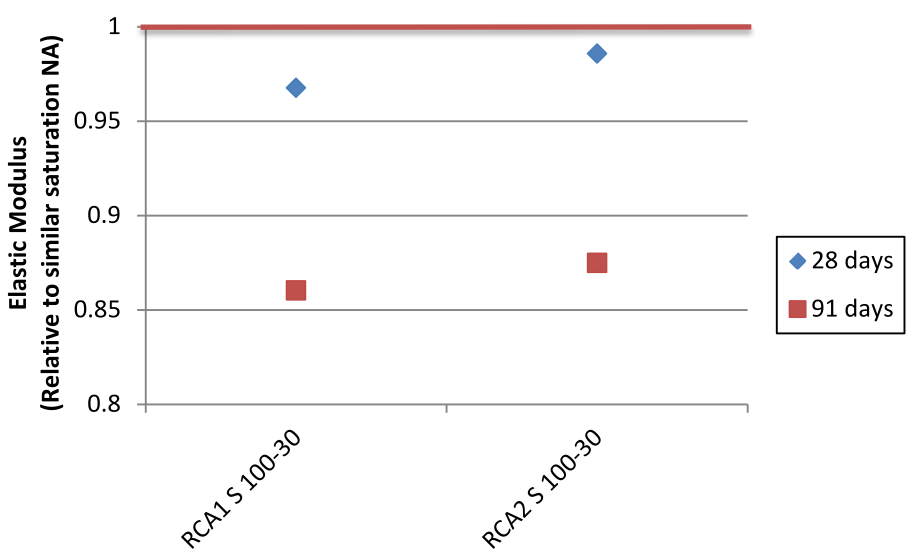

Figure 8: Relative elastic modulus for acceptable replacement level comparison

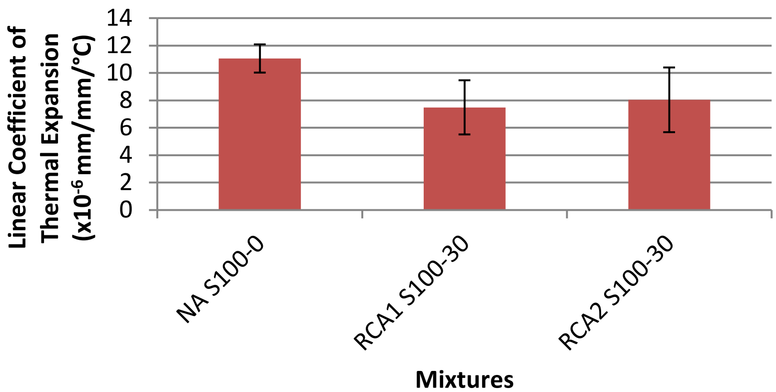

Figure 9: LCTE development for acceptable replacement level comparison at 28 days