Quantification of Recycled Concrete Aggregate (RCA) Properties for Usage in Bridges and Pavements: An Ontario Case Study

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Abstract:

Given the impending shortage of readily available high-quality aggregate and increasing transportation costs, there is continued pressure to use recycled materials in the construction industry as these materials can provide cost effective and environmentally friendly alternatives to natural or virgin aggregates. This study focused on characterizing two Ontario recycled concrete aggregate (RCA) sources and producing new concrete utilizing RCA as coarse aggregate (RCA concrete).

Three aggregate types were investigated, one control virgin aggregate source and two RCAs produced from the crushing of hardened concrete. Each aggregate type was classified according to its size, shape and surface texture. Numerous aggregate tests were performed, including density, absorption, abrasion resistance, adhered mortar content, and crushing value.

Control concrete mixtures utilizing the virgin coarse aggregate source were developed with target strengths of 30 and 50 MPa and target slumps between 75 and 100 mm. The virgin coarse aggregate was then replaced with RCA (by volume) to investigate the effect a particular RCA source had on compressive strength and workability. In both RCA concretes the workability decreased when the virgin aggregate source was replaced with RCA. At higher strength levels (i.e., 50 MPa), the RCA concretes performed similarly to the control mixtures. However, at lower strength levels (i.e., 30 MPa), RCA concretes produced compressive strengths that were 7 to 22% higher than the control mixtures.

The findings and recommendations derived from this research will assist aggregate suppliers, contractors, and engineers in properly assessing whether a particular RCA source is suitable for use in concrete pavement and bridge structures.

1. Introduction

Given the impending shortage of readily-available high-quality aggregate and increasing transportation costs, there is continued pressure to use recycled materials in the construction industry. Demolished concrete that can be crushed and reused either as fill material or in new concrete as aggregate is a viable example of these types of recycled materials. Further benefits can be realized if these new recycled concrete aggregates (RCAs) are produced in close proximity to the site of their future use. Additionally, unlike fly ash, RCA qualifies for both pre- and post-consumer LEED credits [1].

According to the latest report on the State of the Aggregate resource in Ontario published by the Ministry of Natural Resources, 184 million tonnes of aggregate was used in Ontario in 2007. Approximately 75% of the aggregate consumed in Ontario is used in the construction of roads, buildings, sewer and water mains [2]. Out of this total, 13 million tonnes came from secondary or recycled sources used primarily in road construction. However, out of this 13 million tonnes only 18% (2.3 million tonnes) consisted of recycled concrete material used as granular base between 2000 and 2004. The use of RCA as coarse aggregate in structural concrete and pavement applications in Ontario has therefore been very limited. This is mainly due to a lack of experience and knowledge in using these materials in new Portland cement-based concrete applications.

Recently, research has been conducted at the University of Waterloo on the use of recycled concrete aggregates (RCAs) in concrete pavements and road structures [3]. Four 50 metre sections (8.5 metres wide) were paved with concrete that incorporated 0, 15, 30, and 50% RCA replacement of virgin aggregate. The concrete mixtures with 30% RCA as coarse aggregate exhibited similar or improved mechanical properties (i.e., compressive strength, flexural strength, freeze-thaw durability and coefficient of thermal expansion) compared to the conventional concrete mixtures. The test sections were subjected to heavy truck traffic loading as part of a landfill site haul road. After 2 years in service and approximately 3,000, 000 ESALs, all test sections were in excellent condition with performance index values greater than 90.

In 2008, approximately 6000 cubic metres of concrete incorporating RCA obtained from the demolition of the former Stapleton International Airport was used in the new construction of foundations and tilt-up wall panels as part of a 441,000 ft^2 industrial development on the old airport site [4]. This has been one of the very few applications of RCA concrete in structural applications.

2. Scope and Objective of Paper

Although there has been ongoing research into the use of RCA as a structural grade aggregate for use in concrete, the main physical properties of a particular RCA source which have the most significant effect on the resulting concrete properties have yet to be fully categorized and investigated. To fully categorize and distinguish between various RCA sources, a correlation between various RCA characteristics and their influence on the properties of concrete made with RCA must be established. These relationships are necessary to assess a particular RCA source and determine whether it is appropriate for use as coarse aggregate in concrete. The research presented in this paper focuses on explaining the inter-relationships between various coarse aggregate properties and the effect that these properties have on concrete workability and compressive strength.

3. Aggregate Sources and Characterization

3.1 Aggregate Sources

Three aggregate types were used in this research; one natural source which is commercially used in Ontario and two recycled sources. The natural aggregate (NA) source consisted of blended crusher-run limestone and river gravel. The first RCA source (RCA-1) was produced from the crushing of sidewalk, curb, and gutter structures from the Region of Waterloo in Ontario. The second RCA source (RCA-2) was produced from the crushing of decommissioned runway, apron, and terminal structures from Pearson International Airport in Toronto, Canada.

3.2 Shape and surface texture of aggregates

The three aggregate sources were evaluated qualitatively in terms of their shape and surface texture. The nominal maximum particle size of each aggregate type was 19 mm and the gradation adhered to the Ontario Ministry of Transportation guidelines for concrete stone [5]. Both the particle shape and surface textures were characterized according to British Standard BS 812 [6]. Following this standard, the natural aggregate, RCA-1, and RCA-2 were classified as summarized in Table 1. In addition to the information provided in Table 1, RCA-2 contained considerable amounts of deleterious materials such as wood chips, asphalt, metal, plastics, Styrofoam, and tile. These impurities were considered to be part of the RCA-2 aggregate and, as a result, were not removed when used in concrete for this study. Compared to the natural aggregate and RCA-2, RCA-1 appears to have a more roughened surface texture. This may have a significant influence on the bond between the cement paste and the aggregate; a rougher aggregate surface results in higher bond or shear strength at the mortar-aggregate interface [7].

4. Aggregate Physical Properties Testing Results

Various aggregate properties were measured to provide a comparison between both recycled concrete aggregates and the natural aggregate source. Relationships between various aggregate properties and hardened concrete properties were also investigated.

4.1 Adhered Mortar Content of RCA

The adhered mortar portion of the recycled concrete aggregate consists of both hydrated and unhydrated cement particles and the original fine aggregate (sand) where all other particles are considered as original coarse aggregates. Presently, there is no standard test procedure for determining of the amount of adhered mortar on recycled concrete aggregates. Based on current literature, three methods were selected and the results were compared to determine the amount of adhered mortar in the two recycled concrete aggregates (RCA-1 and RCA-2). All adhered mortar content test results are summarized in Table 2. The amount of adhered mortar was calculated for all three methods based on the following expression:

$$\%\ \text{Adhered Mortar} = \frac{\text{Mass of RCA} - \text{Mass of RCA after removal of mortar}}{\text{Mass of RCA}}$$

4.1.1 Nitric Acid Dissolution Method

The method was adapted from the work of Movassaghi [8] and involves immersing the RCA in a 20% (by volume) nitric acid solution and heating it until the adhered mortar starts to dissolve (approximately two hours), leaving behind the original aggregate. However, after the test was completed significant amounts of adhered mortar remained attached to both RCA samples. In addition, the nitric acid dyed some of the aggregates a yellowish colour which may indicate the presence of limestone in the original aggregate. Although significant mass loss occurred, the remaining mortar was still firmly attached to the original aggregates for both the RCA-1 and RCA-2. In an attempt to remove the remaining cement mortar by mechanical friction, the samples were subjected to 15 minutes in the Micro-Deval apparatus. This process however, was unsuccessful at removing the remaining adhered mortar. This suggests that this method dissolved the outer layer or surface of the adhered mortar but failed to breakdown the mortar-aggregate bond. It is possible that longer exposure at higher concentrations of nitric acid could dissolve greater amounts of the remaining cement mortar, although this may also dissolve the original limestone aggregate if present. Although the test was unsuccessful at removing the total adhered mortar amounts it is important to note that significant mass losses of 20% and 32% were recorded for RCA-1 and RCA-2, respectively.

4.1.2 Freeze-Thaw Method

This method combines the use of mechanical stresses and chemical attack to breakdown the adhered mortar of the recycled concrete aggregates. The test procedure was adapted by Abbas et al. [9] from ASTM standard C 88-05, and ASTM standard C666 -03 [10, 11]. A sodium sulphate solution is used to begin the degradation of the adhered mortar; Abbas et al. compared several chemical solutions and found that sodium sulphate was the most effective to degrade the mortar. Representative samples of the RCA-1 and RCA-2 were obtained in the amounts of 1000 g for the 4.75 mm and 9.5 mm size fractions, and 2000 g for the 16 mm and 19 mm size fractions (total of four samples per aggregate type). The samples were then oven dried for 24 hours at

105°C, followed by immersion in a 26% (by weight) sodium sulphate solution. While still immersed in the sodium sulphate solution, the aggregates were subjected to five daily cycles of freezing and thawing consisting of 16 hours at minus 17°C followed by 8 hours at 80°C. A large walk-in freezer and a small oven were used to achieve these temperature ranges. After the final freeze-thaw cycle, the sodium sulphate solution was drained from the samples and the aggregates were washed over a No. 4 (4.75 mm) sieve and placed in an oven for 24 hours at 105°C. The final oven-dry mass was recorded and observations were made.

Upon visual inspection, this method removed more of the adhered mortar than the method based on nitric acid dissolution. Hammering using a rubber mallet to remove the remaining mortar was recommended after the last freeze-thaw cycle was completed. Significant deterioration of the cement paste and the mortar-aggregate bond had been achieved for the smaller aggregate size fractions (4.75 mm and 9.5 mm) and the remaining attached mortar was easily removed by hand. However, upon visual inspection, it was estimated that only between 80 and 90% of the adhered mortar had been removed from the larger aggregate size fractions (16 mm and 19 mm). Similar to the nitric acid dissolution, this method failed to completely remove the adhered mortar even after hammering and mechanical abrasion. Although the test did not completely remove the adhered mortar, significant mass losses of 30% and 41% were recorded for RCA-1 and RCA-2, respectively.

4.1.3 Thermal Treatment Method

The third method used to determine the adhered mortar content for the recycled aggregates involved subjecting the aggregates to large, sudden temperature variations. This method was adapted from the work carried out by Juan and Gutierrez [12]. At temperatures in excess of 400°C, calcium hydroxide dehydration occurs, causing a gradual disintegration of the cement mortar [13]. RCA samples were soaked in water for 24 hours and then placed in a muffle furnace at a temperature of 500°C. After heating for two hours, the RCA samples were quickly removed from the furnace and immediately immersed in cold water causing a sudden reduction in the aggregate temperature and creating internal thermal stresses. Upon cooling, the adhered mortar became very brittle and could easily be broken off by hand. Any remaining adhered mortar was removed using a rubber hammer. Upon visual inspection, this method succeeded to remove nearly 100% of the adhered mortar from the recycled aggregates with recorded mass losses of 46% and 56% for RCA-1 and RCA-2, respectively.

4.1.4 Method Evaluation

After considering all three methods, it is apparent that RCA-2 has a higher amount of adhered mortar than RCA-1, and that the thermal treatment method was most effective at removing the adhered mortar. Based on the thermal treatment results, RCA-2 had 18% more adhered mortar than the RCA-1. Overall, the range of adhered mortar content measured during this study (between 20% and 56%) seems consistent with those reported in the literature [3, 8, 9, 12, 14 and 15].

4.2 Abrasion Resistance

The abrasion resistance of each aggregate was determined using the Micro-Deval method to provide a measurement of aggregate resistance to attrition and abrasion. The test was carried out in accordance with CSA test method A23.2-29A [16]. Test samples were first washed and oven-dried for a 24 hour period at 105°C. A 1500 g oven-dried sample was then prepared using the following gradation percentages: 750 g passing 20 mm sieve and retained on the 14 mm sieve; and 750 g passing the 14 mm sieve and retained on the 10 mm sieve. The final combined mass (approximately 1500 g) was recorded as M_F. After 120 minutes in the Micro-Deval apparatus, the abrasion loss was calculated using the following equation:

$$\text{Abrasion Loss} = \frac{M_F - M_{OD}}{M_F} \times 100\%$$

where, M_{OD} is the ovendry mass of the aggregate after mass loss and sieving. Upon removal from the Micro-Deval apparatus, a noticeable difference in the overall shape and surface textures of each aggregate was observed. In general, all aggregate types experienced mass loss and were observed to be more rounded in shape with smoother surface textures. The recycled aggregates still retained some adhered mortar which had also been rounded by the abrasion action of the Micro-Deval apparatus. Table 5 presents the Micro-Deval abrasion loss values for each coarse aggregate type. As expected, the natural aggregate had a lower abrasion loss than either of the recycled aggregates since it had no adhered mortar. The natural aggregate had a 21% higher abrasion resistance as compared to the RCA-1 and a 46% higher abrasion resistance than RCA-2. In comparison, RCA-2 experienced a 32% higher abrasion loss than the RCA-1.

4.3 Absorption Capacity and Density of Fine and Coarse Aggregates

Natural river sand was used for the fine aggregate for all natural aggregate and RCA concrete mixtures. Table 3 presents the various fine aggregate properties that were tested following CSA A23.2-09 [16]. Table 4 presents the coarse aggregate densities and absorption capacities for all three aggregate types. RCA-2 is the least dense of all the aggregates followed by RCA-1 and the natural aggregate (NA). The absorption capacities of RCA-1 and RCA-2 were significantly higher than the natural aggregate (2.5 and 3.7 times higher, respectively).

4.4 Aggregate Crushing Strength

BS 812-110 [6] was employed to determine the aggregate crushing value (ACV) of each aggregate type to provide a relative measure of the crushing strength of the aggregates. The aggregate samples were sieved to obtain size fractions between 9.5 mm and 16 mm. A steel cylindrical measure was then filled in three equal layers with aggregate and rodded 25 times per layer to obtain the required volume. The initial weight of the aggregate sample was recorded as M_1. The sample was then placed in a hardened steel cylinder and subjected to a crushing load up to 400 kN. The crushed sample was removed and sieved, and the portion passing the 2.36 mm sieve was considered to be the mass loss due to crushing (M_2). Higher values of ACV imply lower aggregate crushing strength. The aggregate crushing value was calculated using the following expression:

$$\mathrm{ACV} = \frac{\mathrm{M}_2}{\mathrm{M}_1} \times 100$$

Noticeable differences in texture, shape and size were observed in each aggregate after crushing. In general, all aggregates became more roughened as many of the rounded and smooth particles were crushed. Figure 1 depicts the test apparatus and the post-crushing appearance of RCA-1. This observation proved to be most evident in the smaller sized particles which became flake-like in shape. RCA-2 appeared to have a higher percentage of fines after crushing than either RCA-1 or the natural aggregate, while the natural aggregate had fewer fines after crushing than both recycled aggregate types. These qualitative observations were consistent with the aggregate crushing values summarized in Table 6.

The natural aggregate has the lowest ACV (highest strength), followed by the RCA-1 and the RCA-2 with the highest ACV (lowest strength). The natural aggregate had a crushing strength that was 21% higher than RCA-1 and 30% higher than RCA-2. This relative difference in ACV values between each aggregate type matched very closely to the relative differences observed in the Micro-Deval abrasion loss values. The ACV results of this study fall within a similar range to those presented in the literature [17, 18].

5. Effect of Adhered Mortar on Various RCA Properties

The trends in adhered mortar test results from this study are consistent with those reported in numerous other studies [15, 17, 18, 19 and 20]. As the amount of adhered mortar increases, density tends to decrease, while the absorption capacity tends to increase with an increase in adhered mortar. This relationship can be explained not only by the amount of adhered mortar, but also by the lower density and higher porosity of the adhered mortar in comparison to that of the natural coarse aggregate particles. As revealed by the values in Table 7, the absorption capacity of the adhered mortar in RCA-2 contributes a larger percentage of the overall absorption capacity as compared to RCA-1. This data was obtained by measuring the absorption capacity of the original aggregates obtained from the thermal treatment method which removed the nearly 100% of the adhered mortar. This suggests that the adhered mortar on the RCA-2 particles is more porous (less dense) than that of the adhered mortar on the RCA-1 particles. The trends in abrasion resistance values may be explained by both the higher amount and lower density of the adhered mortar present in RCA-2 particles. This lower density stems from the more porous structure of the adhered mortar on the RCA-2 particles. Similar to the trend in abrasion resistance, as the percent of adhered mortar increases, the aggregate crushing value decreases (indicating a decrease in crushing strength).

6. Concrete Produced Using RCA as Coarse Aggregate

6.1 Concrete Mixture Proportions and Batching Procedures

Seven concrete mixtures were developed as part of this research program in two separate groups: control and direct replacement mixtures. The two control mixtures used natural coarse aggregate and were proportioned to achieve compressive strengths of 30 and 50MPa with slump values between 75 and 100 mm.

The four direct replacement concrete mixtures were developed by replacing the natural aggregate (100% direct replacement) from the control mixtures with equivalent volumes of RCA-1 and RCA-2 with no other changes to the mixture proportions. The direct replacement mixtures were used to gauge the effect of aggregate replacement on concrete compressive strength and workability. Mixture proportions are referenced with respect to aggregate type (NA, RCA-1 or RCA-2) and concrete compressive strength (30 MPa or 50 MPa). For example, RAC1-30 refers to concrete that was produced using recycled concrete aggregate of type 1 (RCA-1) and was designed for a target compressive strength of 30 MPa. Table 8 summarizes all sets of mixture proportions and their corresponding slump values.

Due to the higher absorption capacity of RCA, the period of time required to reach a saturated surface dry (SSD) condition will be longer than for natural aggregates. Therefore, the additional mixing water reserved for aggregate absorption during mixing may not be fully absorbed by the aggregates in the period between addition of the aggregates to the mixer and placement of fresh concrete. This could result in a significant difference in the theoretical versus effective water-cement ratio and, consequently, introduce another variable that could affect concrete workability and strength. To account for this scenario, aggregates were soaked for 24 hours and then drained immediately prior to batching. This ensured that the highly absorptive recycled concrete aggregates contained additional water above their SSD condition. After 24 hours of soaking followed by draining, the coarse aggregates had some amount of adhered surface moisture (above the saturated-surface dry condition) that was considered to be available as mixing water (see Section 6.2 below for further details). As suggested by Poon et al. [21] the mixture proportions were adjusted to compensate for this additional moisture and to control the effective water-cement ratio.

A pan mixer was used to batch all of the concrete to ensure high shearing action while mixing. Coarse aggregates were added to the mixer along with one third of the mixing water and were allowed to mix for 30 seconds. The sand, cement and the remaining two-thirds of the mixing water were then added and mixed for three minutes followed by a three minute rest. During the three minute rest period the mixer was covered with dampened burlap to mitigate evaporative moisture loss. All ingredients were mixed for a final two minutes and a slump test was performed followed by the casting of 100 mm x 200 mm concrete cylinder specimens. All concrete cylinders were cured at 100% moisture conditions for the first seven days and were then cured in air until they reached their 28 day strength. This curing regime was intended to simulate typical construction site curing conditions.

6.2 Moisture Content of Coarse Aggregates after 24 hours of Soaking

Since all coarse aggregates were pre-soaked under controlled conditions for 24 hours prior to batching, they contained some amount of surface moisture that would be available as mixing water. In order to maintain consistent water-cement ratios, the amount of adhered surface moisture after 24 hours of soaking, followed by draining had to be determined for each aggregate type. A procedure for measuring the amount of adhered surface moisture was developed as outlined below. After 24 hours of soaking the aggregates were drained and their mass was recorded as M_{TOT}. After oven-drying for 24 hours at 105°C, the samples were weighed again, M_{OD}. The amount of adhered surface moisture was then calculated as follows:

$$\%\ \text{Adhered Surface Moisture} = \%\text{Absorption} - \frac{M_{TOT} - M_{OD}}{M_{OD}} \times 100\%$$

Table 4 summarizes the amount of adhered surface moisture for each aggregate type based on 24 hours of soaking followed by draining. The adhered surface moisture content of RCA-1 was 3.5 times and 2.7 times larger than that of the natural aggregate and RCA-2, respectively. This difference may be explained by the more roughened surface texture of the RCA-1 as compared to the smoother surface texture of natural aggregate and granular surface of the RCA-2. Therefore, this measure of adhered surface moisture may be used to provide an indirect quantitative measure of coarse aggregate surface texture.

6.3 Effect of Coarse Aggregate Replacement with RCA on Concrete Workability and Compressive Strength

Slump values, water-cement ratios, and compressive strengths for all concrete mixtures are summarized in Table 8 and Figure 2. A significant reduction in slump of the RCA concrete mixtures in comparison to the natural aggregate concrete mixture was observed. Pre-soaking the RCA-1 and RCA-2 should have eliminated slump loss due to coarse aggregate absorption of mixing water during batching. Thus, the reduced slump values in the RCA concrete mixtures can be attributed to the more angular shape and roughened surface texture of the recycled aggregates that increased the inter-particle friction in the fresh concrete.

After 28 days of curing, the 30 and 50 MPa RCA-1 concrete mixtures achieved compressive strengths that were 22% and 7% higher than the natural aggregate concrete, respectively. The 30 and 50 MPa RCA-2 concrete mixtures produced compressive strengths that were 7% higher and 1% lower than the natural aggregate concrete, respectively. These values are in contrast with trends found in the literature that have reported a decrease in compressive strength when natural aggregate is replaced with RCA [20, 22].

To explain the effect that RCA has on concrete compressive strength, the failure planes of concrete cylinders for each concrete type were observed and classified as being mainly around or mainly through the coarse aggregate. Failure planes that occur around the aggregate indicate that the mortar-aggregate interface or interfacial transition zone (ITZ) is the limiting strength factor. When considering recycled concrete aggregates (i.e., RCA-1 and RCA-2) that contain original natural aggregates and adhered mortar, this suggests that either the old or the new ITZ is the limiting strength factor. Failure planes that occur through the coarse aggregate indicate that the strength of the coarse aggregate itself is the limiting strength factor.

In the 30 MPa concrete samples, the failure plane occurred mainly around the aggregate for all three aggregate types. Recall that all direct replacement mixtures have the same water-cement ratios and, as a result, should have the same new mortar strengths. Therefore, by comparing the compressive strengths of the 30 MPa natural aggregate specimens to the 30 MPa RCA concrete specimens, it appears that the aggregate-mortar bond strength between the new mortar and the RCA (new ITZ) is higher than the aggregate-mortar bond strength between new mortar and the natural aggregate. As suggested by Rao and Prasad [7], this increase in ITZ strength is likely due to the more roughened surface texture of the RCA particles compared to the smoother surface texture of the natural aggregate particles.

In the 50 MPa direct replacement concrete specimens, the failure plane occurred mainly through the aggregate for all three aggregate types (see Figure 3). This suggests that the natural aggregate tensile strength and the original natural aggregate (in the RCA) tensile strength were the limiting strength factors rather than mortar-aggregate bond. Further micro-structural studies are required to confirm this behaviour.

7. Conclusions and Recommendations

The following conclusions are based on the evaluation of the test results presented in this paper:

1. The recycled aggregates (RCA-1 and RCA-2) had lower densities and higher absorption capacities than the natural aggregates mainly due to the lower density of the adhered mortar. These findings agreed closely with the published literature.
2. The thermal treatment method proved to be the most effective at removing adhered mortar from RCA-1 and RCA-2 in comparison to the acid dissolution or freeze-thaw chemical attack methods. In all three methods, RCA-2 had the highest amount of adhered mortar. Based on thermal treatment results RCA-2 had 18% more adhered mortar than RCA-1.
3. In the 30 MPa and the 50 MPa direct replacement mixtures, both the RCA-1 and RCA-2 concrete had lower slump values compared to the natural aggregate concrete. These

lower slump values are due to the more angular shape and roughened surface texture of the RCA.

4. In the 30 MPa direct replacement mixtures, both RCA-1 and RCA-2 concretes had higher compressive strength values than the natural aggregate concrete. This is likely due to the stronger mortar-aggregate bond between the RCA-1 and the new mortar. In the 50 MPa direct replacement mixtures, RCA-1 concrete had slightly higher compressive strength values and RCA-2 concrete had lower compressive strength values than the natural aggregate concrete. In this case, the aggregate strength appeared to be the governing factor. Further investigation into the nature of the mortar-aggregate bond between new mortar and RCA is required to provide further explanation.

Based on the findings of this research the following recommendations are presented to assist researchers, engineers and material suppliers involved with projects that may incorporate RCAs.

1. When determining the percent adhered mortar of a particular RCA source, the thermal treatment method is recommended as it produces the most accurate results.
2. Before specifying a particular RCA for use in structural concrete applications, trial batches are essential in ensuring adequate performance.
3. RCA sources that have been derived from the crushing of older concrete structures that contain negligible amounts of deleterious material can be used as a 100% replacement of virgin coarse aggregate to produce structural-grade concrete. However, to achieve adequate workability, an increase in water content or using a water-reducing admixture may be required. In addition, directly replacing the natural aggregate with RCA will most likely impact its strength and therefore this must be checked during the trial batching stage.
4. The establishment of an RCA properties database that includes a variety of RCA sources not just from Ontario but across Canada could assist researchers and future policy makers involved in the tracking and regulation of these materials.

References

[1] Canadian Green Building Council (CaGBC), "LEED Canada Reference Guide for Green Building Design and Construction", 2010, 718 pgs.

[2] Ontario Ministry of Natural Resources, "State of the Aggregate Resource in Ontario Study", Consolidated Report, February 2010, 34 pgs.

[3] Smith, J.T. "Recycled Concrete Aggregate – A Viable Aggregate Source for Concrete Pavements", Ph.D. Dissertation, University of Waterloo, Waterloo, Ontario, Canada, 2009, 224 pgs.

[4] Bohan, S., "Recycled Concrete Aggregates Rise to the Occasion", Concrete Technology Today, Vol. 1, 2010, pp. 72 – 77.

[5] Ontario Ministry of Transportation, "Material Specification for Aggregates – Concrete", OPSS 1002, 2004.

[6] BS 812: 1990, "Testing Aggregates", British Standards Institute, London, England, 1990.

[7] Rao, G.A. and Prasad, B.K.R. "Influence of the roughness of aggregate surface on the interface bond strength", Cement and Concrete Research, Vol. 32, 2002, pp. 253 – 257.

[8] Movassaghi, R. "Durability of Reinforced Concrete Incorporating Recycled Concrete as Aggregate", MASc Thesis, University of Waterloo, Waterloo, Ontario, Canada, 2006, 159 pgs.

[9] Abbas, A., Fathifazl, G., Isgor, O.B., Razaqpur, A.G., Fournier, B., and Foo, S. "Proposed method for determining the residual mortar content of recycled concrete aggregates", Journal of ASTM International, Vol. 5, No. 1, 2008, 12 pgs.

[10] ASTM C 88 - 05, "Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate", Annual Book of ASTM Standards, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA, 2010.

[11] ASTM C 666/C 666M - 03, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing", Annual Book of ASTM Standards, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA, 2010.

[12] Juan, M.S. and Gutierrez, P.A. "Study on the influence of attached mortar content on the properties of recycled concrete aggregate", Construction and Building Materials, Vol. 23, 2009, pp. 872 – 877.

[13] Zoldners, N.G. "Thermal properties of concrete under sustained elevated temperatures", ACI Materials Journal, SP25-1, Vol. 25, 1971, 31 pgs.

[14] Fathifazl, G. "Structural Performance of Steel Reinforced Recycled Concrete Members", PhD Thesis, Carleton University, Ottawa, Ontario, Canada, 2008, 504 pgs.

[15] Hansen, T.C. and Narud, H. "Strength of Recycled Concrete Made from Crushed Concrete Coarse Aggregate", Concrete International, Vol. 5, 1983, pp. 79 – 83.

[16] CSA A23.2-09, "Methods of Test and Standard Practices for Concrete", Canadian Standards Association, Ottawa, Ontario, Canada, 2009.

[17] Eguchi, K., Teranishi, K., Nakagome, A., Kishimoto, H., Shinozaki, K., and Narikawa, M. "Application of Recycled Coarse Aggregate by Mixture to Concrete Construction", Construction and Building Materials, Vol. 21, 2007, pp. 1542 – 1551.

[18] Sagoe-Crentsil, K.K., Brown, T., and Taylor, A.H. "Performance of Concrete Made with Commercially Produced Coarse Recycled Concrete Aggregate", Cement and Concrete Research, Vol. 31, 2001, pp. 707 – 712.

[19] Etxeberria, M., Vazquez, E., Mari, A., and Barra, M. "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", Cement and Concrete Research, Vol. 37, 2007, pp. 735 – 742.

[20] Chen, H.J., Yen, T., and Chen, K.H. "Use of Building Rubbles as Recycled Aggregates", Cement and Concrete Research, Vol. 33, 2003, pp. 125 – 132.

[21] Poon, C.S., Shui, Z.H., Lam, Fok, H., and Kou, S.C. "Influence of Moisture States of Natural and Recycled Aggregates on the Slump and Compressive Strength of Concrete", Cement and Concrete Research, Vol. 34, 2004, pp. 31 – 36.

[22] Xiao, J., Li, J., and Zhang, C. "Mechanical Properties of Recycled Aggregate Concrete Under Uniaxial Loading", Cement and Concrete Research, Vol. 35, 2005, pp. 1187 – 1194.

Table 1 Aggregate particle shape and surface texture

Aggregate Type	Particle Shape Classification	Surface Texture Classification
Natural	Rounded/Irregular – shaped by a combination of attrition and crushing 	Smooth/Rough – combination of river stone and crushed gravel 
RCA-1	Angular/Irregular – shows fairly well-defined edges at the intersection of plane surfaces 	Rough – noticeable roughened fracture surfaces resembling crushed limestone 
RCA-2	Irregular – resembles crusher run gravel but with a large amount of adhered mortar. Particles are not angular like the RCA-1 	Granular – due to large amount of adhered mortar, more brittle surface, loose adhered rounded mortar particles 

Table 2 Adhered mortar content test results

Test Method	RCA-1	RCA-2	Comments:
Nitric Acid Dissolution	20%	32%	Least effective at removing adhered mortar
Freeze-Thaw	30%	41%	Approximately 80 – 90% removal was achieved
Thermal Expansion	46%	56%	Close to 100% removal of adhered mortar

Table 3 Fine aggregate properties

Fine Aggregate Property	
Fineness Modulus	2.66
Bulk Relative Density (Oven-dry)	2.66
Bulk Relative Density (SSD)	2.70
Absorption %	1.63

Table 4 Coarse aggregate densities and absorption capacities

Coarse aggregate property	NA	RCA-1	RCA-2
Relative density (SSD)	2.70	2.47	2.45
Relative density (Oven-dry)	2.66	2.37	2.31
Oven-dry rodded bulk density (kg/m^3)	1733	1417	1458
Absorption	1.54 %	3.98 %	5.72 %
Moisture content after 24 hours soaking in water	3.26 %	8.95 %	7.92 %
Adhered surface moisture*	1.72 %	4.97 %	2.20 %

***** $M_{adhered} = M_{moisture\ 24h}$ – Absorption %

Table 5 Micro-Deval abrasion loss for each coarse aggregate type

Aggregate type	Micro-Deval abrasion loss
Natural	11.9 %
RCA-1	15.1 %
RCA-2	22.1 %

Table 6 Coarse aggregate crushing values (ACV)

Aggregate type	Aggregate crushing value (ACV)
Natural	18.2
RCA-1	23.1
RCA-2	26.0

Table 7 Absorption characteristics of adhered mortar for RCA-1 and RCA-2

	Natural	RCA1	RCA2
Absorption of original aggregates[1]	1.54%	3.66%	3.44%
Absorption of adhered mortar[2]	N/A	0.32%	2.28%
Portion of Absorption of RCA attributed to adhered mortar[3]	N/A	8%	40%

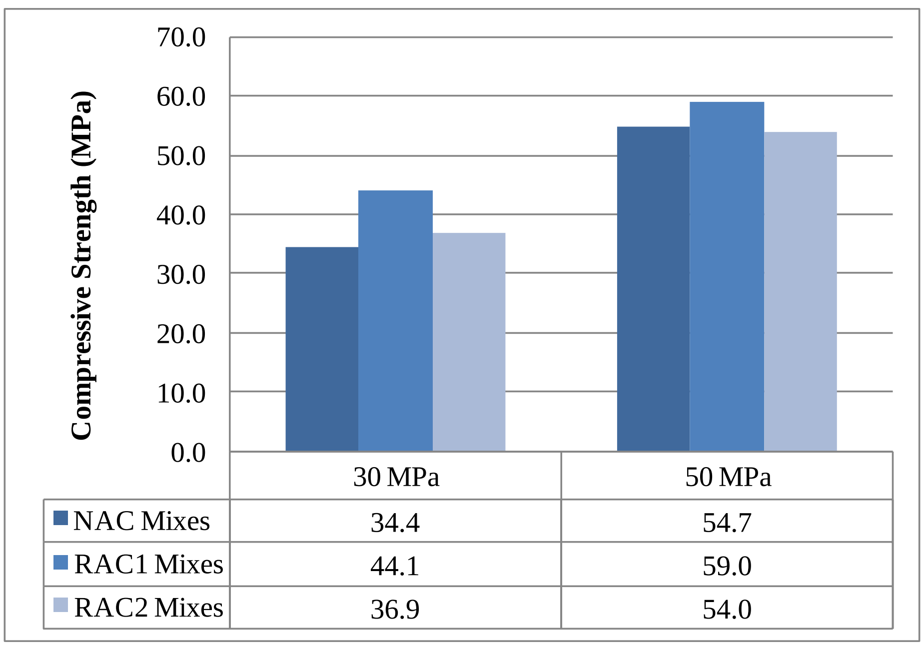
[1] Based on the absorption of the original aggregates obtained from the thermal treatment method.
[2] $M_{adhered\ mortar}$ = Absorption – $M_{original\ aggs}$
[3] Portion of Absorption of Adhered Mortar = ($M_{adhered\ mortar}$/Absorption)x100%

Table 8 Concrete mixture proportions

Material	NAC-30	NAC-50	RAC1-30	RAC1-50	RAC2-30	RAC2-50
Water (kg/m^3)	160	180	160	180	160	180
Cement (kg/m^3)	267	474	267	474	267	474
Coarse Aggregate* (kg/m^3)	1106	1106	975	975	949	949
Fine Aggregate* (kg/m^3)	863	635	863	635	863	635
Water-Cement Ratio	0.60	0.38	0.60	0.38	0.60	0.38
Slump (mm)	90	90	25	35	45	75

*Values reported do not include adjustments for aggregate water absorption

Figure 1 Aggregate crushing value test apparatus and crushed RCA-1



	30 MPa	50 MPa
NAC Mixes	34.4	54.7
RAC1 Mixes	44.1	59.0
RAC2 Mixes	36.9	54.0

Figure 2 Compressive strength results for the 30 and 50MPa strength levels.

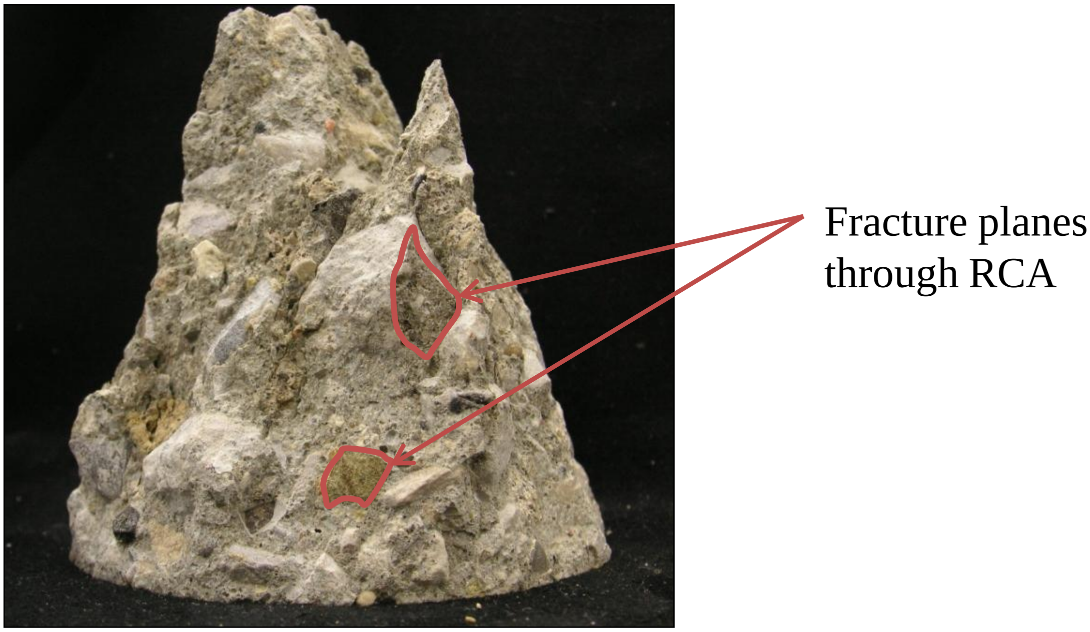


Figure 3 Fracture plane for the 50MPa RCA-1 concrete sample