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The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement

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ABSTRACT

The purpose of this study was to investigate the influence that replacing natural coarse aggregate with recycled concrete aggregate (RCA) has on concrete bond strength with reinforcing steel. Two sources of RCA were used along with one natural aggregate source. Numerous aggregate properties were measured for all aggregate sources. Two types of concrete mixture proportions were developed replacing 100% of the natural aggregate with RCA. The first type maintained the same water–cement ratios while the second type was designed to achieve the same compressive strengths. Beam-end specimens were tested to determine the relative bond strength of RCA and natural aggregate concrete. On average, natural aggregate concrete specimens had bond strengths that were 9 to 19% higher than the equivalent RCA specimens. Bond strength and the aggregate crushing value seemed to correlate well for all concrete types.

1. Introduction

The Canadian concrete and cement industry combined contributed over $3.2 billion to Canada's gross domestic product (GDP) in 2008 and 28.1 million m^3 of concrete were produced [1]. Concrete is composed of cement, coarse aggregate, sand, water and various admixtures. The coarse aggregate comprises between 60% and 75% of the total concrete volume [2]. Due to the high percentage of coarse aggregate used in concrete, a sustainable and economical source of high quality aggregate is essential to the concrete industry. However, recent studies have shown that economically viable natural aggregate sources in some regions, including Ontario, are in decline [3–5]. As a result, the Canadian concrete industry is at risk of facing increased material costs, and will be required to consider alternative aggregate sources. While other high quality aggregate sources may be available, their proximity to centers of urban growth and construction demand may be limited. Recycled concrete aggregate (RCA), produced by crushing concrete from demolished concrete structures is a potential solution to this problem. By reusing demolished concrete structures, it can potentially reduce coarse aggregate costs, resulting in reduced CO_2 emissions associated with aggregate transportation, and reduced construction debris being placed in landfills. Leadership in Energy and Environmental Design (LEED) credits can also be earned towards a particular project that utilizes RCA as a building material. Due to the varied quality of the original concrete and the crushing process used to produce the RCA, its mechanical properties may be inferior to natural aggregate. As a result, the current usage of RCA has been limited to fill material under roadways, building and airport structures. A limited number of studies have investigated the use of RCA in structural concrete applications, whereas investigations of the effect of RCA on the bond strength with reinforcing steel are very limited [6–9]. While it is widely accepted that bond strength is related to concrete compressive strength ($f_c'^{1/2}$), increasing coarse aggregate strength has also been found to increase bond strength. This increase is primarily related to the influence of the coarse aggregate on the concrete tensile strength and fracture energy [10,11]. Accordingly, the potentially inferior mechanical properties of RCA concrete raise concerns regarding the applicability of existing empirical design methods for bond in reinforced concrete made with these materials.

The main objective of this study has been to obtain experimental relationships between various RCA properties, RCA concrete mechanical properties, and the concrete–steel bond strength. A second objective of this study was to develop concrete mixture proportions with 100% RCA as coarse aggregate that achieves equivalent compressive strengths and workability as conventional concrete. These findings will assist aggregate suppliers, concrete producers and engineers in assessing whether a particular RCA source is suitable for use in structural applications.

2. Experimental program

The experimental program was divided into four phases: aggregate testing, concrete mixture proportion development, concrete properties testing, and concrete–steel bond testing. Aggregate properties tested include: water absorption, bulk density, gradation, RCA adhered mortar content, abrasion resistance, and crushing value.

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Aggregates were also classified according to their shape and surface texture. Two series of mixture proportions were developed: constant water–cement ratio mixtures and constant compressive strength mixtures. Concrete tests consisted of slump testing, compressive strength testing, and splitting tensile strength testing at 7 and 28 days. Bond strength and slip were measured using beam-end specimens [12]. The experimental program was structured in this way to demonstrate the inter-relationships between coarse aggregate properties, concrete properties, and concrete-to-steel bond strength.

3. Aggregate testing results and discussion

Various aggregate properties were measured to provide a comparison between both recycled concrete aggregates and the natural aggregate. Relationships between various aggregate properties and hardened concrete properties were also investigated as part of the research program.

3.1. Aggregate sourcing

Three coarse aggregate types were used in this research, one natural source which is commercially used in Ontario and two recycled sources. The natural aggregate (NA) was provided by a local aggregate supplier and consisted of blended crusher-run limestone and river gravel. The two recycled aggregates were produced from the demolition and crushing of existing concrete structures. The first RCA (RCA-1) was produced from the crushing of sidewalk, curb, and gutter structures from the Region of Waterloo in Ontario, Canada. The second RCA (RCA-2) was produced from the crushing of runway, apron, and terminal structures from Pearson International Airport in Toronto, Canada. Natural river sand was used as the fine aggregate for all natural aggregate and RCA concrete mixtures and was graded in accordance with the Ontario Ministry of Transportation guidelines for fine aggregate for use in concrete [13]. Table 3 presents the various fine aggregate properties that were tested following CSA A23.2-09 [25] and the gradation requirements.

3.2. Aggregate shape and surface texture

The three coarse aggregates were evaluated qualitatively in terms of their shape and surface texture. The maximum particle size of each aggregate type was 19 mm and the gradation (Fig. 1) adhered to the Ontario Ministry of Transportation guidelines for concrete stone [13]. Both the particle shape and surface textures were characterized according to British Standard BS 812 [14]. Following this standard, the natural aggregate, RCA-1, and RCA-2 were classified as listed 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 the most 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 [15].

3.3. Adhered mortar content of recycled concrete aggregates

The adhered mortar portion of the recycled concrete aggregate consists of both hydrated and unhydrated cement particles and the original fine aggregate (sand). All other particles are considered to be the original coarse aggregates. At present, there is no standard test procedure for the determination of the amount of adhered mortar on recycled concrete aggregates. However, 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 percent of adhered mortar was calculated for all three methods based on the following expression:

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

3.3.1. Nitric acid dissolution method

This method was adapted from the work of Movassaghi [16] and involves immersing the RCA in a 20% (by volume) nitric acid solution and heating it until the adhered mortar starts to dissolve (approximately 2 h), leaving behind the original aggregate. However, after the test was completed significant amounts of adhered mortar remained attached to both RCA samples. Also, the nitric acid dyed some of the aggregates with a yellowish color which may indicate the presence of limestone in the original aggregate. It should be noted that after nitric acid dissolution, the RCA sample was sieved over a 4.75 mm sieve to ensure only the coarse aggregate component was retained. In addition, any large particles of adhered mortar retained on the 4.75 mm sieve were removed and not considered as coarse natural 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 min in the Micro-Deval apparatus. This process however, was unsuccessful at removing the remaining cement 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 a longer exposure at higher concentrations of nitric acid could dissolve greater amounts of the remaining cement mortar.

Although the test was unsuccessful at removing the total adhered mortar it is important to note that significant mass losses of 20% and 32% were recorded for RCA-1 and RCA-2, respectively.

3.3.2. 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. [17] from ASTM standard C 88–05 [18], and ASTM standard C666-03 [19]. A sodium sulfate solution is used to begin the degradation of the adhered mortar; Abbas et al. [17] compared several chemical solutions and found that sodium sulfate was the most effective at degrading 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 h at 105 °C, followed by immersion in a 26% (by weight) sodium sulfate solution. While still immersed in the sodium sulfate solution, the aggregates were subjected to five daily cycles of freezing and thawing consisting of 16 h at minus 17 °C followed by 8 h 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 sulfate 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 h at 105 °C. The final oven-dry mass was recorded and observations were made. After freeze–thaw treatment, the RCA sample was sieved over a 4.75 mm sieve to ensure only the coarse aggregate component was retained. In addition, any large particles of adhered mortar retained on the 4.75 mm sieve were removed and not considered as coarse natural aggregate. 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

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 

cycle was completed. Significant deterioration of the cement paste and the mortar-aggregate bond had been achieved for the smaller aggregate size fractions (aggregate retained on 4.75 mm and 9.5 mm sieves) 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

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 and gradation requirements.

Fine aggregate property	
Fineness modulus	2.66
Bulk relative density (oven-dry)	2.66
Bulk relative density (saturated surface dry)	2.70
Absorption% (by mass)	1.63

Gradation requirements:

Sieve size	Percent passing
9.5 mm	100
4.75 mm	95–100
2.36 mm	80–100
1.18 mm	50–85
600 mm	25–60
300 mm	10–30
150 mm	0–10
75 mm	0–3

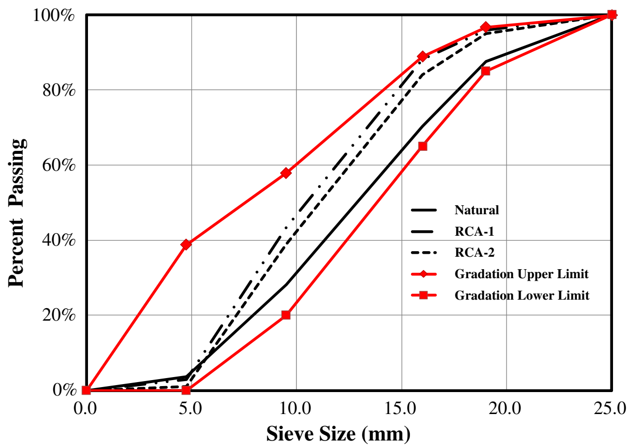

Fig. 1. Aggregate particle size distribution comparison.

the larger aggregate size fractions (aggregate retained on 16 mm and 19 mm sieves). Similar to the nitric acid dissolution, this method failed to completely remove the adhered mortar even after hammering and mechanical abrasion. Although the test was unsuccessful at removing the total adhered mortar, significant mass losses of 30% and 41% were recorded for RCA-1 and RCA-2, respectively.

3.3.3. Thermal expansion 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 [20]. At temperatures in excess of 400 °C, calcium hydroxide dehydration occurs, causing gradual disintegration of the cement mortar [21]. RCA samples were soaked in water for 24 h and then placed in a muffle furnace set to a temperature of 500 °C. After heating for 2 h, 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. The RCA samples were then sieved over a 4.75 mm sieve to ensure only the coarse aggregate component was retained. Any large particles of adhered mortar retained on the 4.75 mm sieve were removed and not considered as coarse natural aggregate. 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.

3.3.4. Discussion of adhered mortar testing results

After considering all three methods, it is apparent that RCA-2 has a higher amount of adhered mortar than RCA-1 and 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. There are two possible explanations for this difference. First, RCA-1 was produced from a lower grade of concrete than RCA-2, and thus, may have contained less cement than the concrete that produced RCA-2. Another explanation for this difference may be due to the type of crushing method used to produce the recycled aggregate. Nagataki et al. [22] reported that as the number of crushing stages during RCA production increases, the amount of adhered mortar decreases. Also, the type of crusher used can influence how efficiently the original concrete is crushed and how much adhered mortar is left on the surface. Impact crushers have been shown to produce RCA with lower mortar content than jaw crushers [23]. Overall, the range of adhered mortar content measured during this study (between 20% and 56%) seems consistent with those reported in the literature [6,16,17,20,24].

3.4. Absorption capacity and density of coarse aggregates

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 (2.6 and 3.7 times higher, respectively). These trends are consistent with the literature [23,24,26–28], and may be explained by the presence of adhered mortar on the recycled concrete aggregates; density tends to decrease, while the absorption capacity tends to increase with an increase in adhered mortar. This relationship can be explained by the lower density and higher porosity of the adhered mortar in comparison to that of the coarse aggregate particles.

3.5. Abrasion resistance by the Micro-Deval method

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 [25]. Test samples were first washed and oven-dried for a 24 h 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, M_F. The sample was then soaked in two of water for 1 h and then placed in the stainless steel Micro-Deval abrasion jar and combined with 5000 g of magnetic 9.5 mm diameter stainless steel balls. The jar lid was fastened and the apparatus was placed in the Micro-Deval machine and subjected to 100 revolutions per minute for 2 h. The samples were then removed from the jar and poured over two superimposed 5 mm and 1.25 mm sieves. Using a magnetic rod, the stainless steel balls and aggregate were separated. Material retained on the 5 mm and 1.25 mm sieves was combined and placed in an oven and the material passing the 1.25 mm sieve was discarded. After 24 h of drying the sample was weighed, M_{OD}. The Micro-Deval abrasion loss was calculated using the following equation:

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

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

Table 4
Coarse aggregate densities and absorption capacities.

Coarse aggregate property	NA	RCA-1	RCA-2
Relative density (saturated surface dry)	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	1539	1458
Absorption% (by mass)	1.54%	3.98%	5.72%
Moisture content after 24 h soaking in water	3.26%	8.95%	7.92%
Adhered surface moisture*	1.72%	5.97%	2.20%

* $M_{adhered} = M_{moisture\ 24h} - \text{Absorption\%}$.

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

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

* Percent mass loss.

Table 6
Aggregate crushing values for the natural aggregate, RCA-1 and RCA-2.

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

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. This may be explained by the higher amount of adhered mortar present in RCA-2 which is a weaker material than natural aggregate. These values fall within in a similar range to other values reported in the literature [16,29].

3.6. Aggregate crushing value

To measure the strength of loose aggregate, BS 812–110 [14] was employed to determine the aggregate crushing value (ACV) of each aggregate type. Aggregate samples were sieved to obtain size fractions between 9.5 mm and 16 mm. A steel cylindrical measure was filled in three equal layers with aggregate and rodded 25 times per layer to obtain the required volume and weight of the aggregate sample was recorded as M_1. The test cylinder was placed on the base plate and the aggregate sample was transferred from the cylindrical measure to the test cylinder in 3 equal layers and rodded 25 times per layer. The surface of the aggregate was leveled in the test cylinder and the plunger was inserted into the cylinder and left to rest horizontally on the aggregate surface. The entire apparatus was placed into a 500 kN capacity test frame where it was loaded at a uniform rate of 40 kN/min up to a load of 400 kN. After the load was removed the aggregate was removed from the test cylinder by hammering with a rubber mallet on the outside wall of the cylinder. The sample was then sieved over a 2.36 mm sieve for 5 min. The aggregate particles passing the 2.36 mm were weighed and recorded as M_2. The aggregate crushing value was calculated using the following expression:

$$ACV = \frac{M_2}{M_1} \times 100$$

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. Fig. 2 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. Before sieving over the 2.36 mm sieve, 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 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 mass loss 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 [26,27].

4. Concrete mixture proportions

4.1. Development of concrete mixture proportions

Ten concrete mixtures were developed as part of this research program. They are divided into three separate groups: control, direct replacement, and strength-based mixtures. The two control mixtures used natural coarse aggregate and were proportioned to achieve compressive strengths of 30 and 50 MPa with slump values between 75 and 100 mm.

The four direct replacement mixtures were developed by replacing the natural coarse aggregate (100% replacement) from the control mixtures with equivalent volumes of RCA-1 and RCA-2 with no other

Fig. 2. Aggregate crushing value test setup and crushed RCA-1.

Table 7
Control (natural aggregate) concrete mixture proportions and test results.

Material	NAC-30	NAC-50
Water (kg/m^3)*	160	180
Cement (kg/m^3)	267	474
Coarse aggregate (kg/m^3)	1106	1106
Fine aggregate	861	633
Water–cement ratio	0.60	0.38
Slump (mm)	90	90
Compressive strength (MPa)	34.4	54.7

* Water content values reported do not include adjustments for aggregate water absorption.

Table 9
Strength-based concrete mixture proportions and test results.

Material	RAC1-30	RAC1-50	RAC2-30	RAC2-50
Water (kg/m^3)	175	190	165	190
Cement (kg/m^3)	243	404	262	500
Coarse aggregate (kg/m^3)	970	970	919	919
Fine aggregate (kg/m^3)	848	672	889	621
Water–cement ratio	0.72	0.47	0.63	0.38
Slump (mm)	80	85	90	85
Compressive strength (MPa)	35.3	53.5	31.5	50.6

*Water content values reported do not include adjustments for aggregate water absorption.

changes to the mixture proportions. The direct replacement mixtures were used to gage the effect of aggregate replacement on concrete compressive strength and workability. The four strength-based mixtures also used 100% replacement of natural aggregate by RCA, however the mixtures w/c ratio, water and cement content were modified to achieve the same strength and workability targets as the control mixtures (i.e., 30 and 50 MPa compressive strengths and slumps between 75 and 100 mm). The strength-based mixtures were developed for two reasons: (1) to determine whether RCA mix proportions could be developed to obtain similar compressive strength and workability to that of natural aggregate concrete and (2), to determine the effect that natural aggregate replacement with RCA has on splitting tensile and bond strength. The proportioning of the strength-based mixtures proceeded systematically by first adjusting the w/c ratio to achieve target compressive strengths of 30 and 50 MPa. The compressive strength data obtained and prior knowledge gained from the direct replacement mixture results assisted in reducing the number of w/c ratio modifications. Once the compressive strength targets (and corresponding w/c ratios) had been achieved, water and cement contents were adjusted (while still maintaining previously determined w/c ratios) until slump values between 75 and 100 mm were achieved. Confirmation batches of all strength-based mixture proportions were then completed to ensure adequate repeatability of fresh and hardened concrete properties. Water reducing admixtures were not used as part of this research, as it was possible to achieve the target slump values through adjustments to the water and cement contents while maintaining the w/c ratio dictated by strength requirements.

Mixtures 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 compressive strength of 30 MPa. Tables 7 through 9 summarize all sets of mixture proportions and their corresponding slump values and compressive strengths.

4.2. Concrete batching procedure

The high water absorption of the RCA can result in changes in workability and the effective w/c ratio of the fresh concrete during mixing and placement due to absorption of the mixing water by unsaturated RCA. The changes in the fresh properties may occur even if the moisture content of the aggregate is known and moisture corrections are applied to the concrete batch quantities since the absorption rate of the aggregate is not instantaneous. In order to minimize this occurrence, typical production practice is to pre-wet the RCA to reduce the amount of moisture absorbed by the RCA during mixing; moisture corrections are still applied for aggregate moisture contents other than saturated-surface dry (SSD). For the purposes of the current research, all coarse aggregates (natural and RCA) were soaked for 24 h and then drained immediately prior to batching to ensure that the aggregate was fully saturated (at or above SSD) to eliminate absorption of the mixing water during concrete production and placement. The aggregate moisture content after soaking was determined (see Section 4.3), and the excess surface moisture (above SSD) was considered to be available as mixing water. Accordingly, the batch proportions were adjusted to compensate for this additional moisture and to maintain a consistent water–cement ratio as suggested by Poon et al., [30]. It should be noted that since water absorption by the coarse aggregate during mixing is eliminated by pre-soaking of the aggregates, it may affect the fresh properties of the concrete in comparison to concrete made with pre-wetted aggregate or where no pre-treatment is applied. However, assuming that the batch moisture corrections are done properly, the effect on the hardened properties of the concrete should not be significant. Nevertheless, the results of this research study are applicable to pre-soaked aggregates, and further study is required to determine the effect, if any, of other aggregate treatment methods on the concrete properties.

A pan mixer was used to batch all 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 s. The sand, cement and the remaining two-thirds of the mixing water were then added and mixed for 3 min 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 2 min and a slump test was performed followed by the casting of 100 mm × 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 (relative humidity of 50 ± 10% at a temperature of 23 ± 2 °C) until they reached their 28 day strength and were tested. This curing regime was intended to simulate typical construction site curing conditions.

Table 8
Direct replacement concrete mixture proportions and test results.

Material	RAC1-30	RAC1-50	RAC2-30	RAC2-50
Water (kg/m^3)*	160	180	160	180
Cement (kg/m^3)	267	474	267	474
Coarse aggregate (kg/m^3)	975	975	949	949
Fine aggregate	863	635	863	635
Water–cement ratio	0.60	0.38	0.60	0.38
Slump (mm)	25	35	45	75
Compressive Strength (MPa)	44.1	59.0	36.9	54.0

* Water content values reported do not include adjustments for aggregate water absorption.

4.3. Moisture content of pre-soaked aggregates

Since all coarse aggregates were pre-soaked for 24 h prior to batching, the moisture content was greater than SSD and surface moisture that would be available as mixing water was present. In order to maintain consistent water–cement ratios, the amount of adhered surface moisture (in excess of SSD) after 24 h of soaking had to be determined for each aggregate type. The procedure for measuring the amount of adhered surface moisture is outlined below. After 24 h of soaking the aggregates were drained and the total mass including absorbed and adhered surface moisture was recorded as M_{TOT}. After oven-drying for 24 h at 105 °C, the samples were weighed again and recorded as, M_{OD}. The amount of adhered surface moisture was then calculated as follows:

$$\%\,\text{Adhered Surface Moisture} = \left(\frac{M_{TOT} - M_{OD}}{M_{OD}}\right) \times 100\% - \text{WaterAbsorption}\%.$$

Table 4 summarizes the adhered surface moisture for each aggregate type. Note that all draining and measurement procedures were performed by the same researcher under the same set of controlled conditions in order to reduce the sample-to-sample variability. These values were used for moisture corrections to the concrete batch quantities.

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.

4.4. Effect of natural aggregate replacement with RCA on mixture proportions

The direct replacement (constant w/c ratio) mixtures were compared to those of the strength-based mixtures (constant f'_c) to determine the influence that a particular RCA type has on water–cement ratio, water demand and cement content for slump values between 75 and 100 mm and compressive strength values of 30 and 50 MPa. The differences in water demand, cement content and water–cement ratio between the RCA concrete mixtures and the control mixtures are summarized in Table 10. In general, water demand increased between 3.1 and 9.4% (by mass) when natural aggregate was replaced by RCA-1 and RCA-2. This range is consistent with similar studies discussed in ACI 555 [31] which had water demand ranges for similar workability of concrete incorporating RCA of 5 to 15% (by mass). This difference is attributed to the more roughened surface texture and angular shape which increase inter-particle friction of the RCA concrete compared to the natural aggregate concrete. Cement contents of both the 30 and 50 MPa RCA-1 strength-based mixtures were 9.0 and 14.8% lower than for the direct replacement mixtures, respectively. This reflects the increase in water–cement ratios of the RCA-1 concrete strength-based mixtures. Cement contents of the RCA-2 concrete mixtures were more similar to the control mixtures due to correspondingly slight variations in water–cement ratios.

The most notable changes between the direct-replacement and strength-based mixtures occurred for the RCA-1 concrete with the target strength of 50 MPa. Specifically, the water–cement ratio increased from 0.38 to 0.47 for the strength-based mixture as the compressive strength was reduced from 59 MPa to 53.5 MPa and the slump was increased from 35 to 85 mm. This increase in water–cement ratio appears to be substantial in relation to the reduction in compressive strength, and illustrates that the strength of the concrete is affected by other factors in addition to the water–cement ratio. The increased water–cement ratio for this concrete resulted primarily from decreasing the cement content from 474 kg/m^3 to 404 kg/m^3, while the water content was increased from 180 kg/m^3 to 190 kg/m^3. Published multi-variable analyses of the relationship between concrete strength and composition show that changes to the water–cement ratio by changing the cement content have a less significant effect on the concrete strength in comparison to changes in the water content [32]. This appears to be consistent with the current study. As well, the aggregate properties (strength and bond) will affect the concrete strength, and may further complicate the relationship between water–cement ratio and strength. Additional discussion of the strength results obtained in this study is provided in Section 5.1. Further investigation into the relationship between concrete composition and strength for RCA concrete is ongoing.

5. Fresh and hardened concrete properties results and discussion

5.1. Effect of RCA on concrete slump and compressive strength

Slump values, water–cement ratios, and compressive strengths for each direct replacement mixture are summarized in Table 11 and Fig. 3. Compressive strength was measured using cylinders with dimensions 100 mm by 200 mm long. Pre-soaking the RCA-1 and RCA-2 should have eliminated any slump loss due to coarse aggregate absorption of mixing water during batching. However, a significant reduction in slump between the natural aggregate mixtures and the RCA mixtures was observed. The lower slump values in the RCA concrete mixtures result from the more angular shape and roughened surface texture of the recycled aggregates which increased the inter-particle friction in fresh concrete.

After 28 days of curing, the 30 and 50 MPa RCA-1 concrete mixtures achieved compressive strengths that were 28% and 8% higher than the natural aggregate concrete, respectively. The 30 and 50 MPa RCA-2 concrete mixtures produced compressive strengths that were 7% higher and 6% 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 [28,33].

To explain the effect that RCA has on concrete compressive strength (assuming that the strength of the mortar phase is constant), 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) which 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 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, have the same mortar strengths. Therefore, by comparing the compressive strengths of the 30 MPa natural aggregate specimens to the 30 MPa RCA direct replacement 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

Table 10
Effect of RCA replacement on strength-based mixture proportions (percent difference from control mixture proportions).

Material	RAC1-30	RAC1-50	RAC2-30	RAC2-50
Water (kg/m^3)	9.4%	5.6%	3.1%	5.6%
Cement (kg/m^3)	−9.0%	−14.8%	−1.9%	5.5%
Water–cement ratio	20.0%	23.7%	5.0%	0%

Table 11
Control variables for the beam-end testing program.

Control variable	Level		
	1	2	3
Aggregate type	Natural	RCA-1	RCA-2
Concrete compressive strength	30 MPa	50 MPa	–
Bonded length	125 mm	375 mm	–

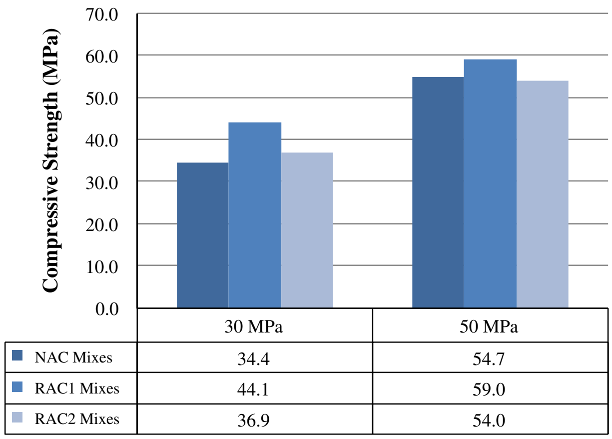

Fig. 3. Compressive strength results for direct replacement mixture proportions.

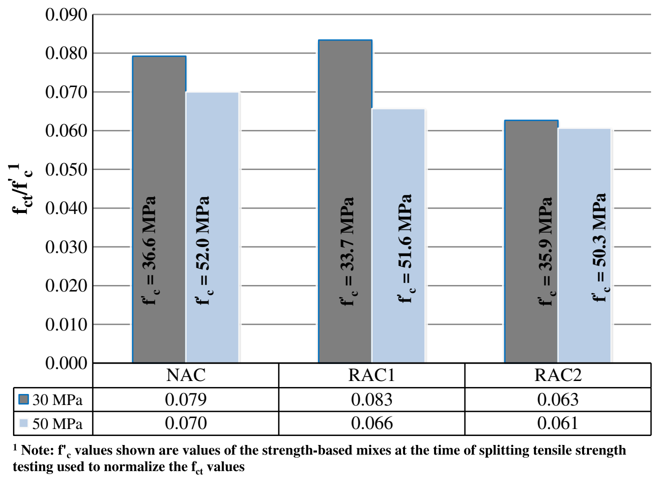

Fig. 4. Relative splitting-tensile strength data for NAC, RAC1 and RAC2.

and Prasad [15], 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. This suggests that the natural aggregate strength and the original natural aggregate (in the RCA) strength were the limiting strength factors rather than mortar-aggregate bond. Further micro-structural studies are required to confirm this behavior.

Another possible effect of RCA on changes in slump and compressive strength could be the inherent variability in the measurement of the water absorption and in-situ moisture content of coarse aggregates as used to determine the moisture corrections for concrete batch quantities; variability in either quantity will affect the true water–cement ratio of the concrete. It is possible that the high water absorption and roughened surface of the RCA could lead to greater variability in the moisture corrections, leading to a higher or lower water–cement ratio than expected. However, it should be noted that after repeated trial batching in the current study, the batch-to-batch variability in slump and compressive strength was fairly low for all mixture types indicating that the variability in the measurement of in-situ moisture content of coarse aggregates was also low. Further investigation is ongoing.

5.2. Effect of RCA on splitting tensile strength

Concrete splitting tensile strength tests were performed on the strength-based concrete mixtures and samples (200 mm long cylinders with a diameter of 100 mm) were cast along with the beam-end specimens. Table 12 summarizes the splitting tensile strength data for the beam-end specimens for each concrete type. Note that the splitting tensile specimens were tested nearly 25 days after the beam-end specimens and thus, their compressive strengths at time of testing were slightly higher than those reported in Table 12.

Table 12
Beam-end bond test data for NAC, RAC1 and RAC2.

Specimen ID[2]	Agg. type	ACV	f_{ct}[3] (MPa)	f'_c[3] (MPa)	τ_b (MPa)	% Diff. in avg. bond strength from NAC specimens[1]
BE-NAC-30-125A	Natural	18.2	2.90	34.5	6.99	0
BE-NAC-30-125B						
BE-NAC-30-375A					5.69	0
BE-NAC-30-375B						
BE-NAC-50-125A			3.64	49.0	6.75	0
BE-NAC-50-125B						
BE-NAC-50-375A					5.86	0
BE-NAC-50-375B						
BE-RAC1-30-125A	RCA-1	23.1	2.81	30.9	5.66	−19.0%
BE-RAC1-30-125B						
BE-RAC1-30-375A					5.04	−11.4%
BE-RAC1-30-375B						
BE-RAC1-50-125A			3.39	47.9	5.98	−11.4%
BE-RAC1-50-125B						
BE-RAC1-50-375A					5.25	−10.3%
BE-RAC1-50-375B						
BE-RAC2-30-125A	RCA-2	26.0	2.25	31.3	5.50	−21.3%
BE-RAC2-30-125B						
BE-RAC2-30-375A					5.00	−12.1%
BE-RAC2-30-375B						
BE-RAC2-50-125A			3.05	49.4	5.86	−13.2%
BE-RAC2-50-125B						
BE-RAC2-50-375A					5.31	−9.4%
BE-RAC2-50-375B						

[1] Negative values indicate a decrease in avg. bond strength compared to NAC specimens.
[2] Specimens have been labeled as follows: BE = Beam-End, RAC1 = Recycled Aggregate Concrete incorporating RCA-1, 50 = compressive strength in MPa, 125 = bonded length in mm, and the letters A and B denote identical specimens A and B.
[3] Compressive strength values are results of strength-based mixtures and were measured at time of testing beam-ends. See Fig. 4 for compressive strength values for splitting tensile specimens.

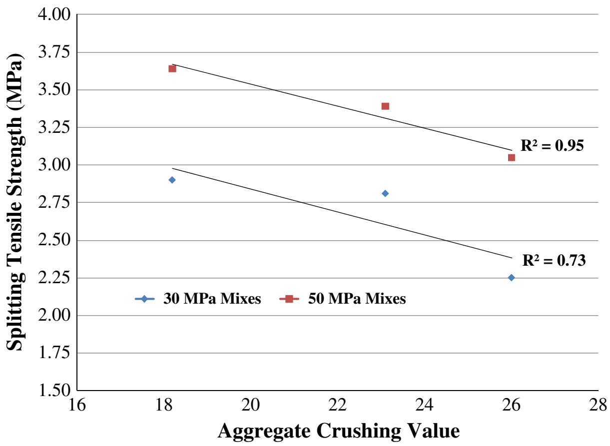

Fig. 5. Interaction between aggregate crushing value and splitting tensile strength.

As a result, splitting tensile strengths are compared on the basis of their normalized values with compressive strength at the time of testing as illustrated in Fig. 4. The 30 MPa RCA-1 concrete specimens had the highest relative splitting tensile strength (0.083) followed by the natural aggregate (0.079) and the RCA-2 (0.063) concrete mixtures. In the 50 MPa mixtures, the natural aggregate concrete had the highest relative splitting tensile strength (0.070) followed by the RCA-1 (0.066) and RCA-2 (0.061) concrete mixtures.

To explain the trends in the relative splitting tensile strength data, the aggregate crushing values for each aggregate type were compared with the relative splitting tensile strengths of the corresponding concrete mixtures. The relationship between the aggregate crushing value (ACV) and the splitting tensile strength is shown in Fig. 5. It is apparent that a strong relationship exists between the ACV and the splitting tensile strength for the 30 MPa and 50 MPa concrete samples as noted by the R^2 values of 0.73 and 0.95, respectively. Based on the difference in R^2 values at the 30 and 50 MPa strength level, it appears

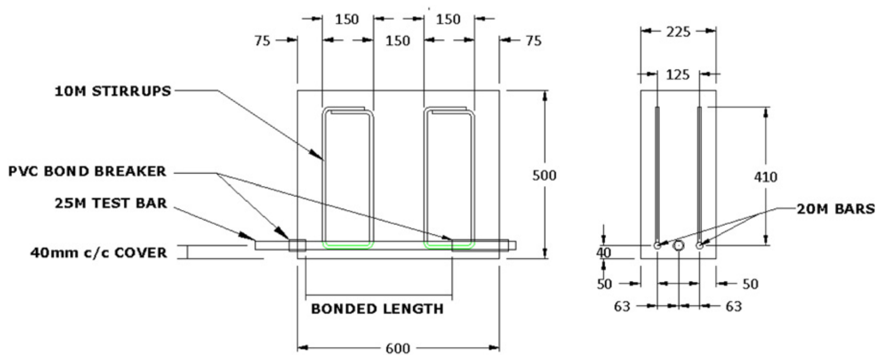

Fig. 6. Beam-end specimen dimensions and reinforcement details.

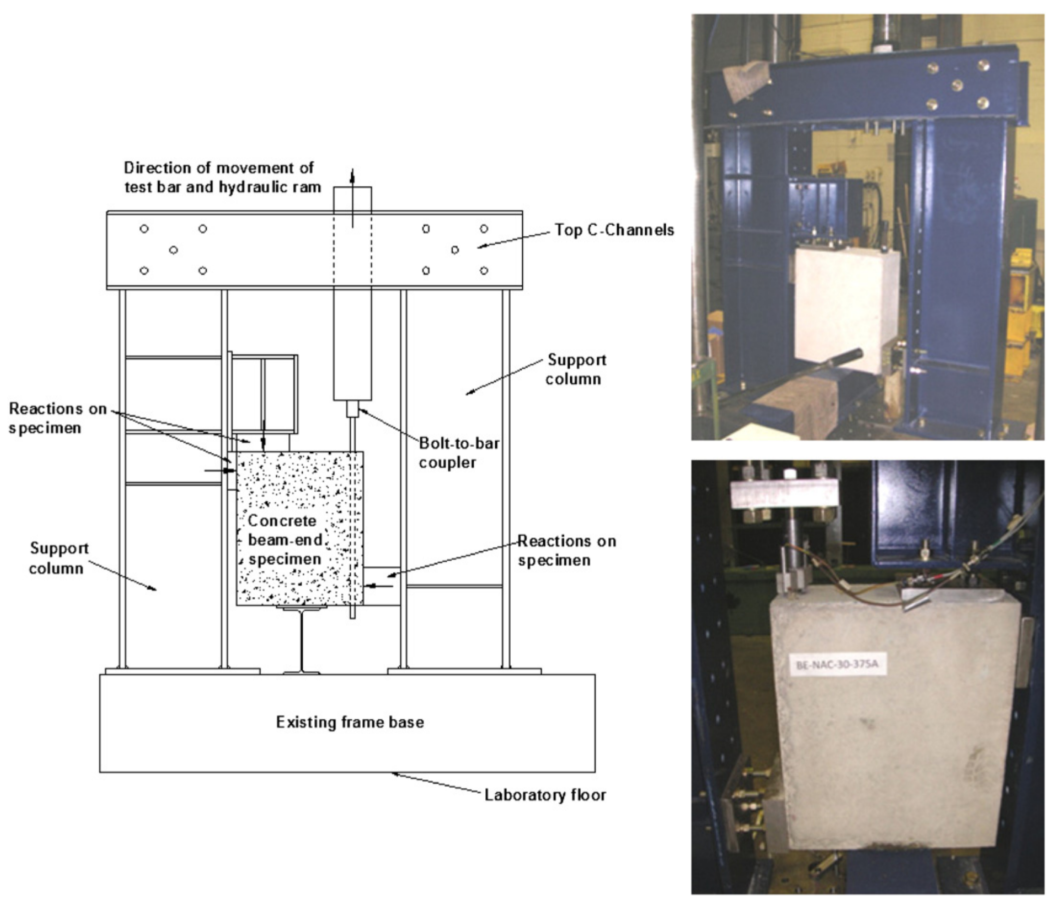

Fig. 7. Beam-end test frame apparatus schematic, completed test frame and beam-end specimen.

that splitting tensile strengths become more sensitive to the coarse aggregate strength or ACV at higher compressive strength levels. At higher compressive strengths, the lower water–cement ratio creates a stronger mortar, and the coarse aggregate strength governs the overall strength of the concrete. At lower compressive strengths (i.e., 30 MPa), the mortar–aggregate bond strength tends to govern the concrete splitting tensile strength. By considering the effect that ACV has on splitting tensile strength for higher concrete strengths (i.e., 50 MPa), a comparison based on ACV can be made between a particular RCA source and a natural aggregate source. This comparison could be used as an early indicator of how concrete produced with RCA will perform, with respect to its splitting tensile strength, compared to concrete produced with natural coarse aggregate.

6. Beam-end bond test results and discussion

The main testing program involved batching all three concrete types to produce 24 beam-end specimens. Concrete clear cover and reinforcement bar diameter were both kept constant at 30 mm and 25.2 mm, respectively. These values were chosen to represent typical values for interior exposure concrete and for a beam-end cross-section of the size selected. The main reinforcement consisted of a 25 M deformed bar with bonded lengths of 5 bar diameters (125 mm) and 15 bar diameters (375 mm). All beam-end control variables are summarized in Table 11. Only the strength-based mixtures (constant compressive strengths of 30 and 50 MPa) were used when casting beam-end specimens.

6.1. Beam-end specimens

Beam-end specimens with dimensions of 600 mm × 500 mm × 225 mm were chosen based on guidelines provided in ASTM A944-05 [12]. Unlike pullout specimens, beam-end specimens are intended to replicate the concrete and reinforcing steel stress states present at the end of a reinforced concrete flexural member where both the tension steel and surrounding concrete are placed in tension. Compared to full-scale beam specimens, beam-ends are relatively simple to construct and test. To prevent conical failure at the loaded-end, bond-breakers were installed at the specimen surface. Shear reinforcement was placed in the same plane as the longitudinal reinforcement so as not to intercept any longitudinal splitting cracks resulting from bond failure and therefore eliminate any confinement effects. The beam-end cross section and its reinforcement layout are presented in Fig. 6.

6.2. Test setup and procedure

The design of the beam-end testing frame was adapted from the suggested setup presented in ASTM A944-05 [12]. A vertical, versus horizontal, pullout direction was chosen such that existing testing equipment could be used. The test frame configuration is shown in Fig. 7. Design of the test frame was stiffness-based, rather than strength-based,

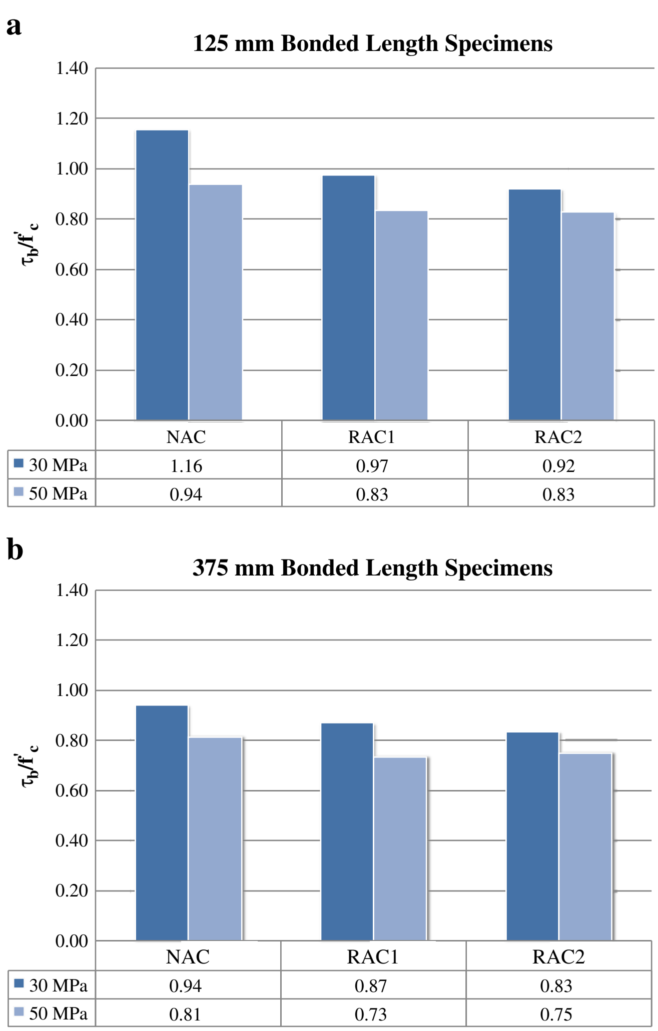

Fig. 8. a,b Average bond stress data for NAC, RAC1, and RAC2. (a) 125 mm bonded length specimens. (b) 375 mm bonded length specimens.

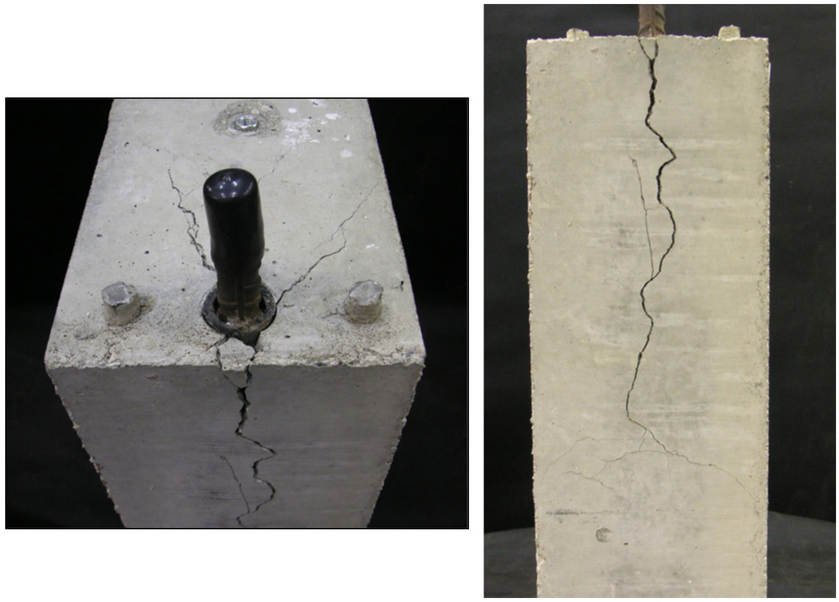

Fig. 9. Typical splitting failure of beam-end specimen (BE-RAC2-50-375A).

to ensure displacements of the test frame would be negligible in relation to bar slip. Once the specimen was aligned in the frame, the threaded-end of the bar was connected to a Lenton bolt-coupler system to provide a mechanical connection to the actuator (applied load), eliminating the possibility of slip between the bar and coupler that may occur in wedge grip systems. Three linear variable differential transformers (LVDTs) with an accuracy of 0.01 mm used to measure slip. Two LVDTs were mounted to the loaded-end of the bar to obtain an average measure of the loaded-end slip, and the other was mounted to the bottom of the specimen to measure free-end slip.

All slip displacement values were measured relative to the concrete specimen. Load was measured using a 500 kN load cell, and the experiment was conducted using a closed-loop servo-hydraulic testing system under axial displacement control. A constant axial displacement rate of 0.3 mm/min was used to capture the post-slip behavior of each specimen and to ensure that slip or other failure did not occur less than 3 min after the start of the test.

6.3. Bond stress and slip results

Aggregate crushing values, splitting tensile strengths, compressive strengths, and average bond stresses are reported in Table 12. The splitting tensile and compressive strengths reported in Table 12 for the RCA specimens are based on strength-based mix designs. Each average bond stress value reported represents the average value of two identical beam-end specimens.

Average bond stress values, normalized to compressive strength, for the 125 mm and 375 mm bonded lengths are summarized in Fig. 8a and b, respectively. The natural aggregate concrete beam-end specimens with bonded lengths of 125 mm had average bond strengths that were 11.4 to 19.0% higher than the RCA-1 concrete specimens and 13.2 to 21.3% higher than the RCA-2 specimens.

The natural aggregate concrete beam-end specimens with bonded lengths of 375 mm had average bond strengths that were 10.3 to 11.4% higher than the RAC-1 specimens and 9.4 to 12.1% higher than the RAC-2 specimens. In general, the natural aggregate concrete beam-end specimens achieved higher bond strengths than the RCA concrete specimens at both the 30 and 50 MPa compressive strength levels. On average, the RCA-1 concrete specimens achieved higher bond strengths than the RCA-2 specimens except for the case of specimen type BE-RAC2-50-375 which had an average bond strength of 5.31 MPa compared to 5.25 MPa for the equivalent RCA-1 concrete specimen type, BE-RAC1-50-375. Splitting failures occurred in all specimens (Fig. 9) regardless of the compressive strength or bonded length. This type of failure was expected for the level of concrete cover provided.

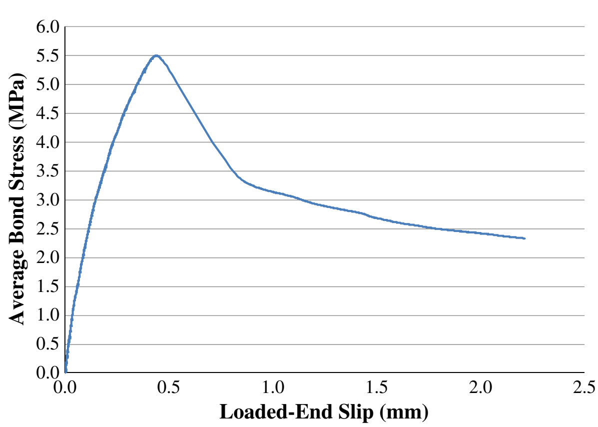

Fig. 10. Typical average bond stress vs. slip response for a beam-end specimen (BE-RAC2-50-375A).

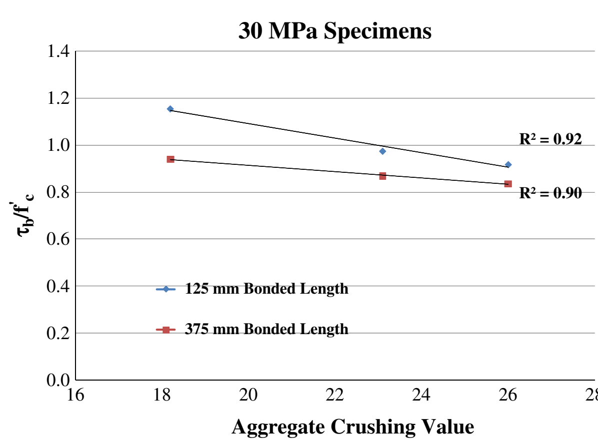

Fig. 11. Interaction between aggregate crushing value and average bond stress (30 MPa samples).

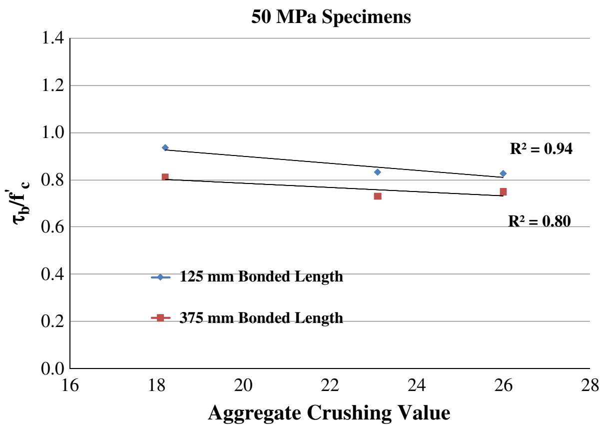

Fig. 12. Interaction between aggregate crushing value and average bond stress (50 MPa samples).

Fig. 10 is a typical bond stress vs. slip plot and depicts the load-slip relationship. As the bond stress increases, the curve starts to increase non-linearly until the bond capacity of the beam-end is reached, at which time the load suddenly drops off and begins a gradual decent. The remaining bond capacity after initial slip can be attributed to the friction between the bar ribs and the surrounding concrete.

6.4. Effect of RCA properties on bond strength

Contrary to the noted relationships in the literature [34] average bond stress did not relate very closely with $f'^{1/2}_c$ or $f'^{1/4}_c$ or the splitting tensile strength (interaction plots not shown). Instead, a strong relationship between the aggregate crushing value and the average bond stress was observed as illustrated in Figs. 11 and 12 for the 30 MPa and 50 MPa specimens, respectively. Note that average bond stress values for each specimen were normalized with respect to their corresponding compressive strengths measured at the time of testing. In the 30 MPa specimens, the average bond strength appears to correlate well with the ACV as demonstrated by R^2 values of 0.92 and 0.90 for the 125 mm and 375 mm bonded lengths, respectively. Similarly, the 50 MPa specimens had R^2 values of 0.94 and 0.80 for the 125 mm and 375 mm bonded lengths, respectively. These trends suggest for various values of bonded length and concrete compressive strength that there may be a relationship between the average bond stress and the crushing strength of coarse aggregate (ACV). As suggested by other researchers [10,11], this may be due to the influence of course aggregate on fracture energy of concrete which has been related to the bond strength between concrete and steel reinforcement. Higher strength aggregates have been shown to produce concretes with higher fracture energies [10] and higher splice strengths [11]. The lower aggregate crushing values of the RCA-1 and RCA-2 may explain why the RCA concrete beam-ends had lower bond strengths than the natural aggregate concrete beam-ends, however further research and a larger data set is required to confirm this trend.

7. Conclusions

Aggregate test results for several aggregate types including one natural aggregate and two different recycled concrete aggregates have been presented. Three series of mixture proportions were developed which included control mixtures, direct replacement or constant water–cement ratio mixtures, and strength-based mixtures with target compressive strengths of 30 and 50 MPa. Twenty-four beam-end specimens were tested to assess the influence of recycled concrete aggregate on bond between reinforcing steel and concrete. The results of this study have added to the current state of knowledge the effect of RCA on bond strength. It has also highlighted fundamental aggregate properties that may be used in the quality assessment of a particular RCA being considered as an alternative coarse aggregate for use in structural concrete applications.

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

(1) The recycled aggregates (RCA-1 and RCA-2) had lower densities and higher water absorption capacities than the natural aggregates mainly due to the higher porosity of the adhered mortar. These findings agree 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 mixture proportions, both the RCA-1 and RCA-2 concrete had lower slump values compared to the natural aggregate concrete. These lower slump values are likely 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 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.
(5) To achieve similar compressive strength and workability, the RCA-1 and RCA-2 concrete mixtures required between 3.1 and 9.4% additional mixing water compared to the natural aggregate concrete mixtures. This range agreed closely with the published literature and is due to the increased inter-particle friction present between the more angular shape and roughened surface texture of the RCA.
(6) To achieve similar compressive strength and workability, the RCA-1 concrete mixtures required a 9.0 to 14.8% reduction in cement content compared to the natural aggregate concrete mixtures. The RCA-2 concrete mixtures required similar cement contents to the natural aggregate concrete.
(7) A strong relationship was found between ACV and splitting tensile strength. As the ACV increases, the splitting tensile strength of the concrete decreases. Splitting tensile strengths become more sensitive to the coarse aggregate strength or ACV at higher concrete compressive strengths.
(8) Natural aggregate concrete beam-end specimen bond strengths were 10.4 to 19% higher than RCA-1 and 9.4 to 21.3% higher than RCA-2 concrete specimens. Contrary to published literature, average bond stress did not correlate very well to the splitting tensile strength, f'_c, $f'^{1/2}_c$ or $f'^{1/4}_c$. However, there appears to be a relationship between the ACV and the average bond strengths for all concrete types and bonded lengths. As the ACV increases (indicating weaker strength coarse aggregate), the bond stress decreases. This relationship may be linked to the influence of coarse aggregate crushing strength on the fracture energy of concrete.
(9) While this study investigated only two sources of RCA, these findings do indicate that replacing natural aggregate with RCA, can have a significant impact on bond with reinforcing steel even for similar concrete strengths.

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