ONE-YEAR PERFORMANCE EVALUATION OF MUNICIPAL CONCRETE SIDEWALKS USING COARSE AND FINE RECYCLED CONCRETE AGGREGATE

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Abstract

This paper summarizes the results of an experimental study on Class C2-32 concrete pavements (as specified by the Canadian Standards Association in CSA A.23.1) for an air-entrained sidewalk mixture. Results are reported with respect to mechanical properties and durability aspects of recycled aggregate concrete, compared to its conventional virgin aggregate equivalent. The impacts of replacing virgin aggregate with Recycled Concrete Aggregate (RCA) are discussed in this paper. Mixes were evaluated with replacements of coarse aggregate up to 30% (by volume) and with 20% replacement of both fine and coarse aggregate. Overall performance of recycled coarse aggregate in new concrete was found to be equivalent to that of conventional concrete. Fresh and hardened properties of mixes incorporating coarse recycled aggregate exhibited equivalent performance to the benchmark design, while mixes incorporating the full granular RCA were within acceptable limits, showing a minor decrease in flexural strength and increased susceptibility to salt scaling. Mixes were first evaluated in a laboratory setting prior to implementation in a municipal commercial field trial which continues to display positive performance after an initial year of exposure.

1 Introduction

Concrete is the most commonly used construction material in the world. The demand for natural aggregates to develop concrete is extremely high, and at the same time, demolished concrete waste is rapidly rising in the world (Yang et. al., 2008). The ability to recycle concrete, and expand its use in new production, would present further opportunities for sustainable development.

A common reluctance exists amongst ready-mix suppliers to incorporate Recycled Concrete Aggregate (RCA) into mix designs due to lack of understanding on this material. An apparent knowledge gap stems from the fact that RCA has multiple source feeds. These can produce different physical properties in the material, and thus diverse quality and composition (Gokce, 2003), unless properly controlled/screened in production through a strict quality control system. Major RCA sources include concrete rubble from building demolition and infrastructure projects, as well as return-to-plant concrete; each type having its own benefits and limitations. As sources vary in any region, and significantly across countries, variations in material and quality control are expected, and thus different RCA mixture proportioning methods had been previously evaluated to ensure proper performance of RCA concrete (Knaack & Kurama, 2013).

As a result of demolition activities, demolition RCA has the potential to be contaminated with asphalt, glass, wood chips, wiring, and steel reinforcement, among other things present in the demolition site. The presence of contaminants has been found to increase the variability in compressive strength values in RCA Concrete (Ulloa et. al., 2013). Return-to-plant concrete is typically considered a cleaner source than demolished concrete structures (Obla & Kim, 2009) as the contamination potential from returned loads is virtually non-existent. The drawback here is that this source is derived from hardened returned concrete, as well as washout concrete being disposed from ready-mix trucks and collected in wash-out ponds, resulting in higher fines content. The properties of a given RCA mix would be dependent on the properties of the source RCA (Yang et al, 2008).

The drawbacks of RCA use in concrete have been studied globally (Poon et. Al, 2004) (Dhir et. Al. 1998), and as a result, replacement in structural applications is typically restricted to 30% (Kou & Poon, 2012). Previous research performed has indicated that RCA concrete is in fact suitable for structural applications (Xiao et. al., 2006), and can even produce 50 MPa structural concrete with similar durability properties as virgin aggregate concrete (Shayan & Xu, 2003). With just some minor adjustments to the mix design proportioning, flexural performance of reinforced RCA concrete had even been found to be equivalent or superior to that of conventional virgin aggregate concrete (Fathifazl et. al., 2009). Global efforts are continuous on this topic. Studies in New Zealand using recycled concrete for sidewalks show that utilizing RCA in these applications is technically feasible (Park, 1999). In Australia, approximately 50% of waste rubble is recycled back into RCA (Shayan & Xu, 2003).

Various researches have pointed out drawbacks in the material, and more research has found parameters to overcome these drawbacks globally. This research project focused on addressing the use of RCA in concrete produced to meet Canadian climate conditions. Other research has indicated that through proper air-entrainment practice, the use of RCA had been found to provide equivalent results to that of conventional virgin aggregate concrete (Salem et. al., 2003). Such air-entrained mixtures are required in the Canadian climate and were evaluated in this study.

The research project utilizes concrete rubble materials collected from building demolition sites, infrastructure projects, and returned concrete processed into a RCA material with a maximum sizing of 20mm minus. This paper presents field results of an investigation into the mechanical and durability properties of plant-produced moderate strength class C-2 mixes (in accordance to CSA A23.1). Investigation was carried out with volumetric (virgin) aggregate replacement levels at 10%, 20% and 30% for coarse aggregate, and 20% (overall) replacement of both coarse and fine virgin aggregate with RCA in concrete trial mixes. A standard control mix was produced and placed alongside the different trial mixes in sidewalk panels for comparative analysis.

2 Research Significance

This research program incorporates varying percentages of RCA products in 32 MPa (4641 psi) C2 sidewalk mixes (in accordance with CSA A23.1) in the City of Mississauga, Ontario, Canada. This is the first field trial in Ontario of municipal sidewalks incorporating RCA exposed to winter freeze-thaw cycles and frequent salting. Successful demonstration and durability performance paves the way for broader acceptance of the use of RCA in concrete for this type of application. This research is meant to further data available for establishing RCA quality characteristics and permitting the use of RCA in concrete in the Canadian market.

3 Experimental Program

The CSA standard mix; 32 MPa (4641 psi) Class-C2, was tested for fresh, hardened, and durability performance. Two varying gradations of RCA were used at various replacement levels in this study. The following tests were performed on all field mixes; slump, measured air, density, compressive strength, flexural strength, linear drying shrinkage, air void system analysis, Rapid Chloride Permeability (RCP), resistance to freezing and thawing, as well as salt (surface) scaling. The five field mixes tested are as follows: (1) Standard Control, (2) 10% Coarse RCA, (3) 20% Coarse RCA (4) 30% Coarse RCA and (5) 20% (20-0, Granular) RCA. Mixes were designed to have equivalent overall aggregate volumes. Coarse RCA (20-7mm) was volumetrically substituted for virgin limestone at replacement levels of 10%, 20% and 30%. The granular RCA mix was designed to replace 20% of the overall aggregate volume, with the 20-7mm portion substituting for limestone and the 7-0mm portion substituting natural sand. RCA was commercially graded to meet the gradation specifications for OPSS 1002 (Ontario Provincial Standard Specification) concrete stone and Granular A as set out in OPSS 1010.

4 Materials

General Use (GU) Portland cement equivalent to ASTM Type 1 and Ground Granulated Blast Furnace Slag (GGBFS) were used in the production for all concrete mixtures. The chemical composition and physical characteristics of these cementing materials are presented below in Table 1. Mixes incorporated natural limestone and sand with a specific gravity (SSD) of 2.751 and 2.675, respectively. Coarse RCA and granular RCA were both derived from commercial production and tested for performance characteristics as shown in Table 2. Blends incorporating coarse RCA were tested for physical properties, as can be seen in Table 2. The sand and fine RCA (7-0 mm) portions were blended to incorporate 20% fine RCA. Further grain size distribution of all aggregate materials as well as the FA blend, are displayed in Table 3.

Table 1 - Aggregate blend and cementitious properties

CSA Laboratory Testing (A23.2-2A)					Cementitious Properties		
CSA A23.2-2A Test	Spec	Blend (RCA CA:VLS)			Chemical	Cement	Slag
		10:90	20:80	30:70	SiO_2 (%)	19.6	38.4
% Micro-Deval Abrasion Loss	14/17 max	9.1	10.2	11	Al_2O_3 (%)	4.9	10.64
% Flat & Elongated	20 max	5	3	3	Fe_2O_3 (%)	3.1	0.79
Accelerated Mortar Bar	0.150 max	0.045	0.043	0.048	TiO_2 (%)	-	0.71
Magnesium Sulphate Soundness	12 max	0.6	0.5	1.1	CaO (%)	61.4	34.2
% Wash Loss (80 µm)	2 max	0.5	0.6	0.7	MgO (%)	3	6.94
Clay Lumps	0.3/0.5	0.07	0.01	0	SO_3 (%)	3.6	0.2
Low Density Particles	0.5/1	0.01	0.03	0.39	S^{2-} , %	-	1.1
LA Abrasion	50	21.3	22.6	23	Alkalis as Na_2O (%)	0.7	0.16
% Absorption	2 max	1.2	1.54	1.9	LOI (%)	2.3	3.09
Relative Density Bulk	-	2.692	2.661	2.621	Blaine (cm^2/g)	3870	4500
Relative Density SSD	-	2.724	2.72	2.67	+ 45 µm (%)	3	1
Relative Density Apparent	-	2.782	2.775	2.758	Density (g/cm^3)	3.15	2.93

Table 2 - Aggregate properties

CSA Laboratory Testing (A23.2-2A)								
Material	Virgin Limestone	Virgin Sand	RCA - Coarse	RCA - Fine	Blend (RCA CA:VLS)			Blend (RCA-FA: VS)
					10:90	20:80	30:70	20:80
% Absorption	0.89	1.18	5.4	12.99	1.2	1.54	1.9	3.1
Relative Density Bulk	2.727	-	2.362	2.019	2.692	2.661	2.621	2.533
Relative Density SSD	2.751	2.675	2.489	2.281	2.724	2.72	2.67	2.612
Relative Density Apparent	2.795	-	2.707	2.737	2.782	2.775	2.758	2.749

Table 3 - Aggregate gradations (% passing)

Sieve (mm)	RCA CA (20-7 mm)	RCA (20-0 mm)	20 mm Limestone	Concrete Sand	20% RCA-FA:80% VS
26.5	100	100	100	100	100
19	91	94	93.8	100	100
16	80.6	88.9	75.2	100	100
13.2	65.9	82.4	59.6	100	100
9.5	39.8	70.9	31.1	100	100
6.7	17.5	60.4	12.8	100	100
4.75	6.9	52.6	5.3	99.8	99.7
2.36	5.9	40.5	1.8	88	83.6
1.18	5.9	31.1	0.8	67.1	58
0.6	5.9	23.2	0.8	44.6	38.6
0.3	5.9	14.9	0.8	21.9	21
0.15	5.9	9.3	0.8	8.5	9.4
0.075	2.5	6.1	0.8	2.3	4.3

5 Test Methodology

Fresh properties testing was performed including measured air, tested in accordance with ASTM C231, slump (ASTM C143) and concrete temperature (ASTM C1064). Hardened properties of all mixes were evaluated by casting field specimens as outlined in the testing protocol displayed in Table 4. The compressive strength of concrete was tested on cylindrical concrete specimens in accordance with ASTM C39. Beams were cast for flexural strength testing under 3-point loading in accordance with ASTM C78. RCP tests and hardened Air Void System (AVS) testing were done on cylinders of the same dimension in accordance with ASTM C1202 and ASTM C457, respectively. The RCP cylinders were cured and tested at both 28 and 56 days. AVS testing was performed after 28 days of curing. Prisms were cast for drying (linear) shrinkage and freeze-thaw resistance and tested in accordance with ASTM C666 procedure-A. Slabs for salt (surface) scaling were cast in accordance with ASTM C672. To better understand field conditions, all specimens were cured for 1 day in the field while covered with an insulating blanket to ensure proper curing temperatures in field conditions. After 24 hours, specimens were demoulded and cured appropriately in accordance to the aforementioned testing specifications. Cylinders were kept in a curing room maintained at 100% RH with a temperature range of 20 ± 2’C.

Table 4 - Hardened and durability properties protocol

Hardened and Durability Testing Protocol				
Parameter	Specimen Type	Specimens per mix	Total # of specimens	Dimensions (mm)
Compressive strength	Cylinder	18	90	100x200
Flexural strength	Beam	2	10	540x155x155
Drying shrinkage	Prism	2-3	12	285x75x75
Air void system	Cylinder	1	5	100x200
Rapid Chloride Permeability	Cylinder	4	20	100x200
Freeze-Thaw Resistance	Prism	2-3	12	285x75x75
Salt (Surface) Scaling	Slab	2-3	12	300x300x82

1mm = 0.0393701 inch

6 Results and Discussion

6.1 Fresh Properties

Fresh properties were tested on site for each mix and similar overall behavior was observed, regardless of RCA replacement level. All mixes exhibited slump in the range of 80-100mm, and air contents ranged from 6-7.3% on site, as displayed in Table 5.

Table 5 - Measured fresh properties

Property	Units	Spec	Control	10% RCA	20% RCA	30% RCA	20% (20-0) RCA
Fresh Density	kg/m^3	-	-	2313	2309	2260	2254
Concrete Temp	C	-	25	21.5	20.8	21	21.5
Measured Air	%	5-8	7	6.9	7.2	7.3	6
Slump at site	mm	50-110	100	100	90	90	80

A reduction in air content was observed as the granular RCA (20-0mm) was introduced. It is theorized that the micro-fines in the full graded RCA have occupied some of the pore volume in the paste matrix, yielding slightly lower air content. However, the fresh air content remained within specifications for all mixes. Although the lowest slump value (80mm) was observed in the mix containing 20-0mm RCA, it was noted by the contractor that this particular mix had similar placement and finish-ability as the other trial mixes. In fact, surface finishing was noted to provide a smoother finish, contributable to the excess fines present in the granular product. No significant difference was observed in terms of slump and workability between the various mixes, regardless of RCA replacement level. This was also noted in research done by Levy & Helene (2004).

The 20% (20-0mm) granular RCA mix displayed the lowest slump on site (80mm), possibly due to the higher absorption of the RCA fines present in the 20-0mm graded RCA used in this mix. The moisture condition of RCA has previously been shown to impact the initial slump of Recycled Aggregate Concrete (RAC) (Poon et al, 2004) and in another study, Poon et. al (2007) observed that RCA, when used above the Saturated-Surface-Dry (SSD) state, actually increased slump. However, another study by Yang et. al (2008) found that mixing conditions and mix proportioning would be the main parameters to control the initial slump of RAC and determined that initial slump was only slightly affected by the relative absorption of aggregates.

Fresh air content was observed not to be affected by the inclusion of coarse RCA up to 30%. It should be noted that the stockpiles for both RCA grading were pre-wetted to achieve a stable moisture state, just slightly higher than the water-saturated surface dry (SSD) state, to ensure consistent mix properties, and reduce the potential for plastic shrinkage.

6.2 Hardened Properties

Compressive Strength

At the 7 and 28-day mark, equivalent compressive strength was obtained for all mixes. Early compressive strength at 1 day indicated a differential of 4.1 MPa between the mixes, most likely due to variations in field curing. By 28 days, under controlled curing conditions, the spread had decreased to 2.83 MPa, indicating equivalent later-age strength development, regardless of RCA replacement level. This is further represented below in Table 6 and Figure 1, where the ultimate compressive strength at 90 days ranged from 37MPa (30% RCA) to 40.3 MPa (20% RCA).

Table 6 - Compressive strength development

	Compressive Strength, MPa (psi)				
Age	Control	10% RCA	20% RCA	30% RCA	20% (20-0) RCA
1-Day	12.53 (1817)	14.99 (2174)	16.47 (2389)	13.91 (2017)	12.37 (1794)
3-Day	17.66 (2561)	19.56 (2837)	20.12 (2918)	18.39 (2667)	19.14 (2776)
7-Day	24.06 (3490)	23.66 (3432)	24.52 (3556)	24.67 (3578)	23.98 (3478)
14-Day	28.66 (4157)	27.57 (3999)	28.54 (4139)	28.23 (4094)	28.31 (4106)
21-Day	30.06 (4360)	30.04 (4357)	33.66 (4882)	31.67 (4593)	30.22 (4383)
28-Day	31.99 (4640)	32.39 (4698)	34.82 (5050)	32.73 (4747)	32.13 (4660)
56-Day	33.93 (4921)	34.6 (5018)	37.36 (5419)	36.89 (5350)	34.91 (5063)
90-Day	39.9 (5787)	38.64 (5604)	40.34 (5851)	36.97 (5362)	N/A

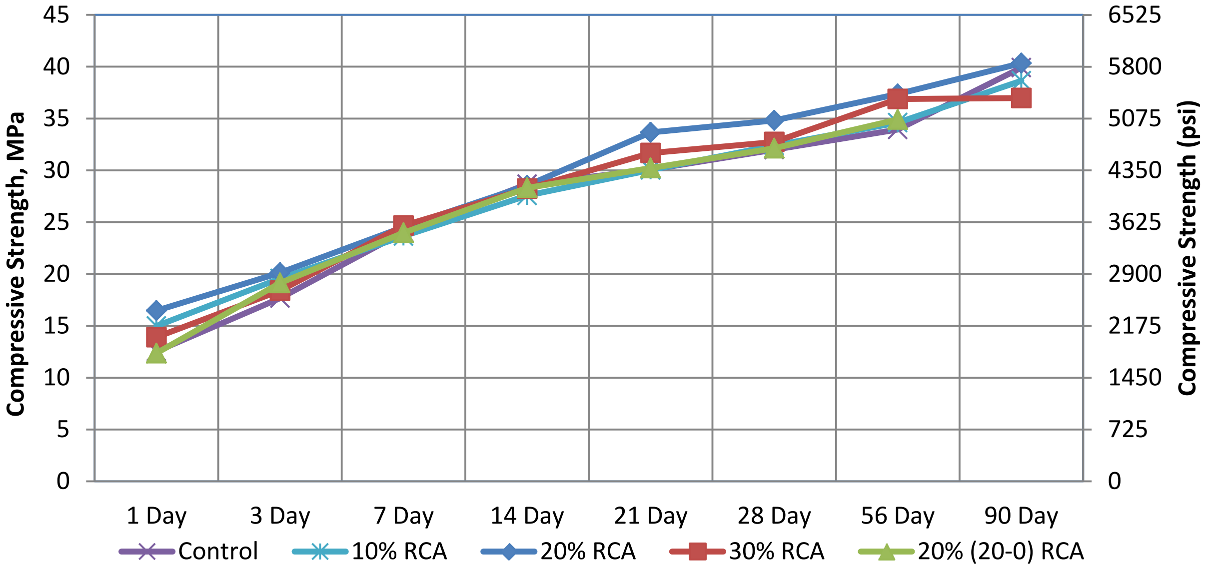

Figure 1 - Compressive strength development

C2 mixes are classified by CSA (A23.1) to achieve a minimum of 32 MPa (4641 psi) by 28 days. Mixes containing up to 30% coarse RCA were able to achieve this requirement by 28 days and the 20% granular RCA mix was also observed to provide equivalent performance. It is well documented that the aggregate quality influences final concrete strength. In this program, equivalent compressive strength results confirm that the RCA material used in these mixes was of sufficient quality, and as such, did not impact the overall mix performance in terms of compressive strength. Other researchers observed similar results and found that RCA of high quality has no impact on compressive strength development of RAC (Marinkovic et al, 2010). Levy and Helene (2004) observed a similar trend in mixes designed in the range of 20-40MPa (2900-5800 psi).

Flexural Strength and Hardened Density

Flexural strength tests displayed only minor reductions when RCA is introduced relative to the control. The control mix had the highest flexural strength at an average value of 6.6 MPa (957 psi) and the 10% coarse RCA mix was the lowest, averaging 5.46 MPa (791 psi). The mixes with higher proportions of coarse RCA (20% & 30%), as well as the granular RCA mix, all achieved approximately 6.1MPa (884 psi), decreasing the gap between the control and the RCA mixes to 0.5 MPa (72.5 psi), as can be seen in Figure 2. Similarly, Park (1999) had concluded that flexural strength of concrete made using recycled aggregates will be less than their virgin aggregate counterpart.

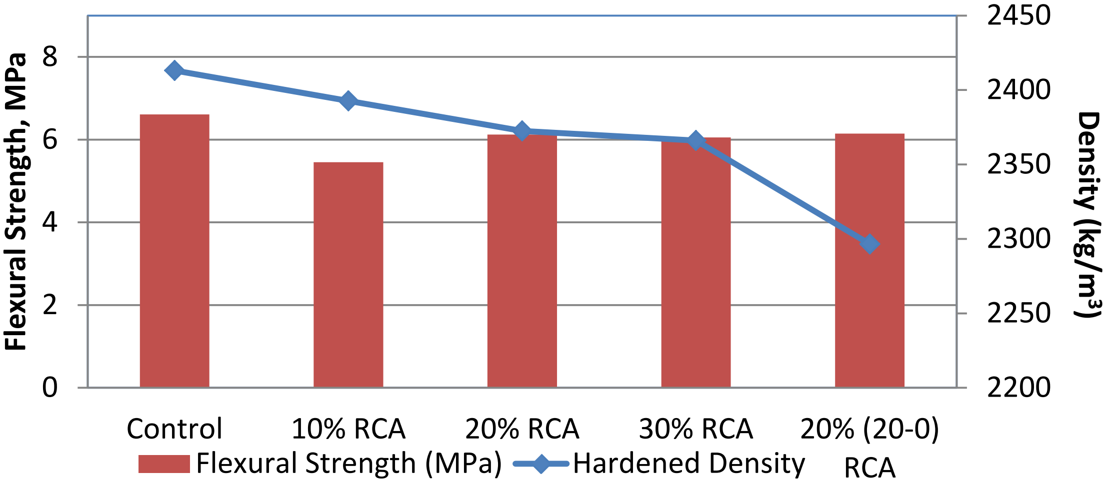

Figure 2 - Flexural strength and hardened density

Generally, a relatively small reduction in flexural strength is observed for all RCA mixes, regardless of replacement level or grading. With the exception of the 10% coarse RCA mix, which had a 17.4% reduction in flexural strength, relative to the control, the average decrease in flexural strength was approximately 10%. Various research also found negligible differences in flexural strength for RAC mixes compared to their NAC counterpart (Limbachiya et al, 2004) (Gholamreza et al, 2009) while some have seen decreases in flexural strength (Park, 1999) (Sonawane & Pimplikar, 2013). The Interfacial Transition Zone (ITZ) between the old RCA mortar-paste and new paste is commonly seen as the weak link, contributing to lower flexural strength (Xiao et al, 2012). It is to be noted that hardened air-voids testing in the 10% RCA mix revealed the highest air content, which is believed to contribute to the reduced flexural strength performance.

Hardened density results indicate that, as the RCA is introduced, a reduction in density occurs proportionally with increasing RCA content. The lower density of the RCA material is the primary reason for this finding, as also found previously by Park, (1999).

6.3 Durability Properties

Air Void System (AVS)

AVS testing results met the requirements set out by CSA A23.1 and OPSS 1350. All coarse RCA mixes showed increased hardened air voids content to the control, relative to the control mix, as seen in Table 7.

Table 7 - Air void system results

Sample Identification	Paste Content, %	Total Air Content, %	Specific Surface (mm^{-1})	Spacing Factor (mm)
Control	24.89	6.2	44.96	0.09
10% RCA CA	25.56	7.7	44.93	0.074
20% RCA CA	26.59	7	40.8	0.093
30% RCA CA	25.26	6.5	40.62	0.095
20% (20-0) RCA	28.44	6.2	37.44	0.119

The presence of the residual mortar, which generally has a high porosity, is thought to be the primary reason for the additional air voids. It should be noted that most concrete mixes in Canada are air-entrained, due to the fluctuating climate, increasing the likelihood that the source concrete for RCA was air-entrained. In a similar study, Gokce et. al (2003) found no issues with freeze-thaw durability in mixes incorporating RCA from an air-entrained source concrete. However, the 20-0mm RCA mix displayed a similar hardened air-void system to the control. The distribution of micro-fines in this mix is thought to have occupied some of the pore volume of the paste matrix, offsetting the additional porosity in the attached mortar-paste in the coarse RCA portion. The otherwise entrained residual mortar would have lost these air pockets when it was crushed and ground to the finer particles.

Freeze-Thaw [ASTM C666]

Freeze-thaw resistance testing was carried out for the full recommended 300 cycles. It was observed that all concrete mixes displayed equivalent performance in freeze-thaw resistance, achieving durability factors in excess of 95%, as shown in Figure 3. This far outweighs the 60% limit set forth by ASTM C666. No noticeable difference or significant damage was observed on the specimens.

Combined with the hardened AVS results, shown in Table 7, it may be concluded that the concrete has an adequate air void system of appropriate maturity, thus preventing critical saturation of water. In line with the findings for hardened air voids, the freeze-thaw tests show equivalent performance in terms of the durability factor. This is indicative that the air void system is well distributed and can accommodate freeze-thaw cycles. Similar studies had found that RAC mixes had durability factors in excess of 90%, indicating little to no deterioration under freeze-thaw attack (Limbachiya et al, 2004) (Gokce et. Al., 2003).

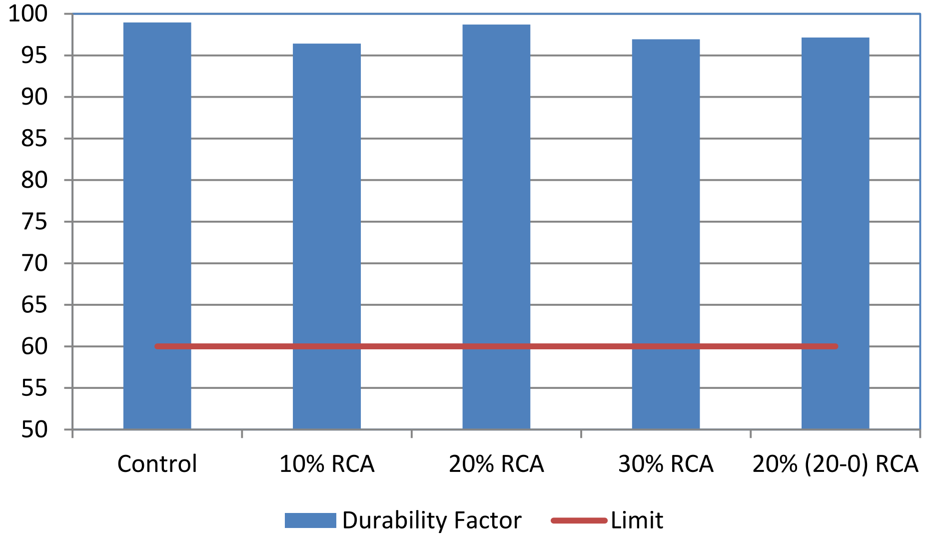

Figure 3 – Resistance to freezing and thawing after 300 cycles

Length Change of Concrete (Linear Shrinkage) [RMCAO Modified Method]

Up-to-date results displayed equivalent shrinkage from all field-cast specimens, as seen in Figure 4. The 20% RCA mix appears to have lower drying shrinkage relative to the other mixes. However, it is noted that many factors can influence shrinkage, such as the proportion of coarse aggregate in the sample used to cast the specimen, the total paste content, as well as the current moisture in the concrete at the time of casting. All other specimens display equivalent results relative to the control mix. It was expected that linear drying shrinkage would be higher for the RCA mixes, as seen in previous unpublished trials by the authors conducted in controlled laboratory trials, given the higher porosity of the attached mortar phase and thus overall higher paste content. However, the difference was not observed at the field level.

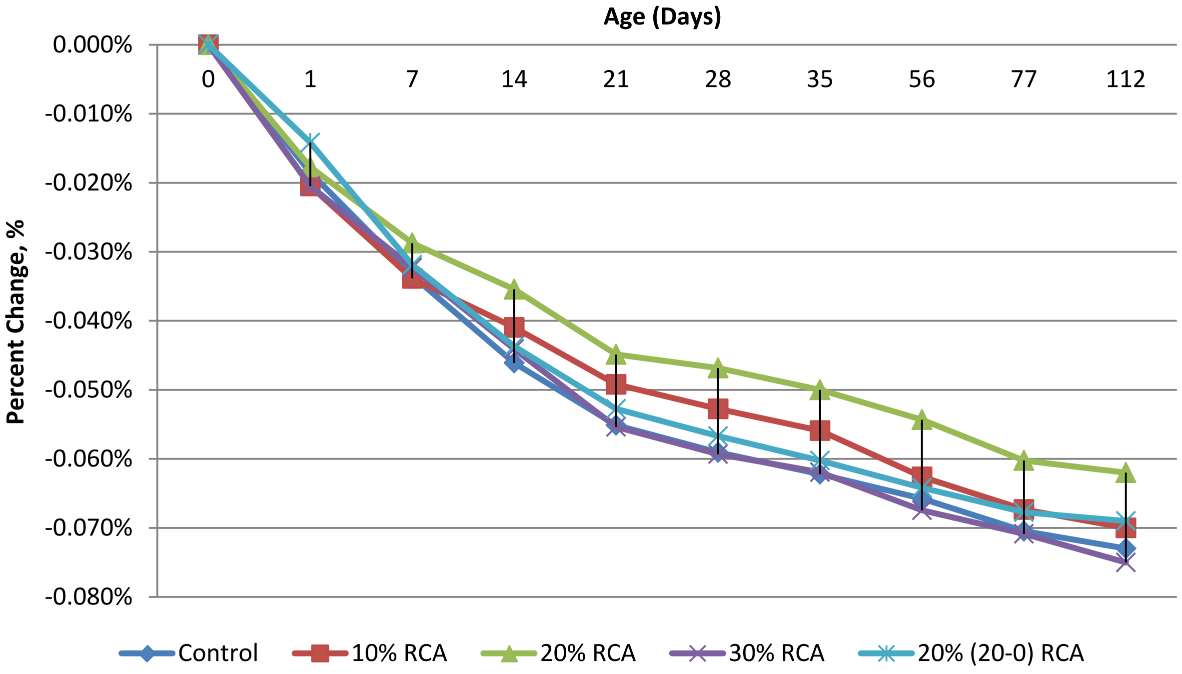

Figure 4 - Linear Drying Shrinkage Results (RMCAO Modified Method)

It should be noted that the concrete industry in Ontario does not support the field testing for linear shrinkage due to the higher variability of field samples when compared to strictly controlled laboratory samples (Ready-Mix Concrete Association of Ontario, 2010). This study further confirms such suspicions and thus does not recommend standard specimen casting and testing for field specimens.

Rapid Chloride Permeability [ASTM C1202]

RCP testing revealed relatively consistent results in the performance of all mixtures, regardless of RCA replacement level. At the 28-day mark, the control, 10% RCA, and 20% RCA mixes fell at the borderline threshold for “moderate” penetrability, as seen in Figure 5. Other mixes incorporating a slightly higher replacement level (30% coarse RCA and 20% granular RCA), fell into the “moderate” range for RCP resistance in accordance to ASTM C1202. It was observed that specimens at 56 days all exhibited similar RCP results, as seen in Figure 6. Based on the RCP testing performed at the later age, where hydration is assumed to have mostly completed; only a slight increase in penetrability of chloride ions was observed in the mixes containing RCA, potentially due to the lower density of these mixes. However, all specimens fell into the “Low” range for the electrical indication of resistance to chloride ion penetrability (1000-2000 Coulombs). This is likely due to the incorporation of GGBFS, which is well known to improve durability properties of concrete. It helps to densify the paste matrix, making it more difficult for chloride ions to pass through the structure. This later-age reaction and densification contributes to the long-term durability performance of concrete, as observed in these results. It is to be noted that under CSA, there are no specification limits for this mix classification, yet testing was still performed as a relative indicator for potential further trials on exposure classes with such requirements.

Table 8 – Rapid chloride permeability testing results

Mix Description	Control	10% RCA	20% RCA	30% RCA	20% (20-0) RCA
Average Coulombs (28d)	2063.5	2070.0	1698.0	2404.5	2226.5
Average Coulombs (56d)	1369.5	1613.5	1537.0	1481.5	1474.0

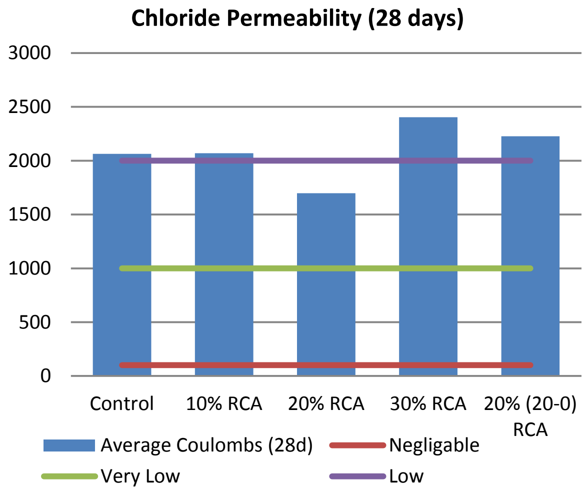

Figure 5 - RCP Results (28-Day)

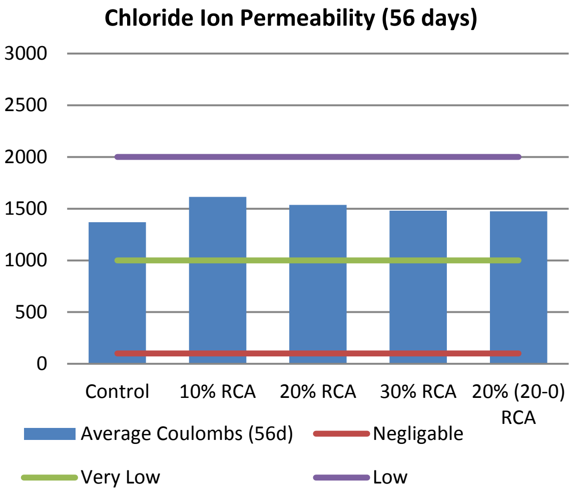

Figure 6 - RCP Results (56-Day)

Scaling Resistance of Concrete Surface Exposed to Deicing Chemicals [ASTM 672]

Results for salt surface scaling vary between RCA types incorporated in the mixes. After 50 cycles, the control mix and coarse RCA mixes exhibited only very slight scaling with a corresponding visual rating for these specimens reported at ‘1’. The specimens for the granular RCA mix had a visual rating indicating slight scaling ‘2’, and correspondingly, had a higher mass loss compared to all other mixes. The visual change from zero to fifty cycles is illustrated below for the control mix (Figure 7), 30% coarse RCA mix (Figure 8) and 20% Granular RCA mix (Figure 9).

The mass lost from salt scaling tests have shown that the coarse RCA mixes are slightly more prone to scaling under aggressive conditions than the non-RCA control. Even if coarse RCA is used, micro-fines in the form of dust still exist and adhere to the surface of these larger particles. These micro-fines are of lower density and it is well known that additional cement is needed to fully coat fine particles, ensuring a strong bond. It would appear that the micro-fines present in the RCA mixes have resulted in higher mass losses under scaling. After 50 cycles, relative to the control mix, a 200% increased mass loss for mixes incorporating coarse RCA and 400% increased mass loss when incorporating the granular RCA is observed. Nonetheless, all coarse RCA mixes had a visual rating equivalent to the control and the granular RCA mix indicated slight scaling. It is noted that ASTM C672 does not require mass loss to be reported, and follows the visual rating system.

Figure 7 - Control mix at 0 cycles (top) and 50 cycles (bottom)

Figure 8 - 30% coarse RCA at 0 cycles (top) and 50 cycles (bottom)

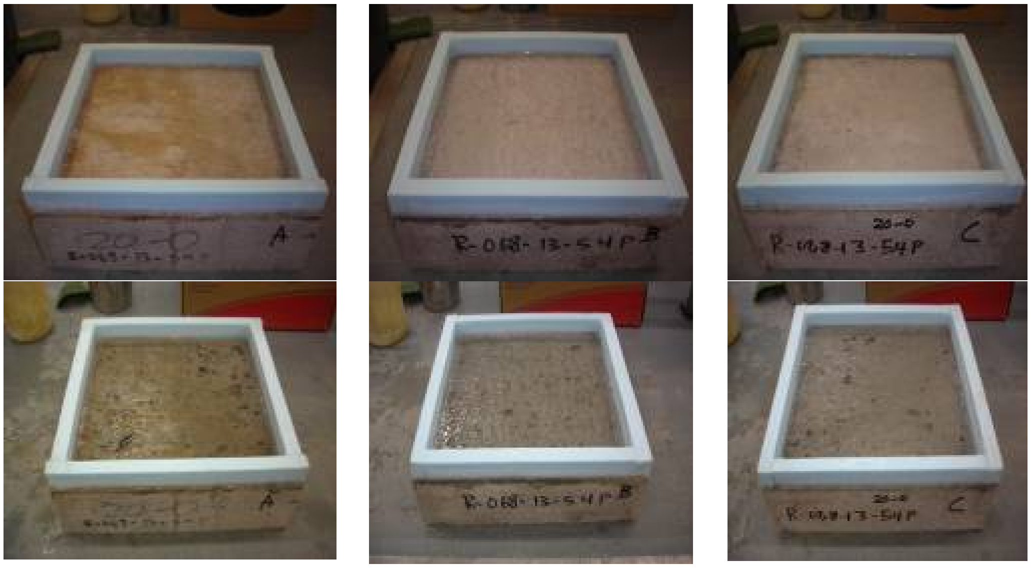

Figure 9 - 20% granular RCA at 0 cycles (top) and 50 cycles (bottom)

7 Field Observations

7.1 Construction Observations

A few observations were noted by the contractor concerning the placement of the slabs during construction. Regardless of the mix, either a RCA replacement mix or the control, consistency was observed. The contractor also noted that there was no difference in the workability of the coarse aggregate RCA replacement mixes compared to the control. In fact, the granular RCA mix (20% replacement) seemed to hold a more defined broom finish than the other mixes including the control. Overall the RCA mixes showed equivalent workability and equivalent or better finish control.

7.2 One Year Inspection

Visual inspection was completed one year after casting on each of the sidewalk slabs to evaluate the overall performance of each mix. Throughout the year, the slabs underwent 98 freeze-thaw cycles and 66 salting trips. Visual field performance evaluation indicated no significant difference between RCA and control panels. Though minor occurrences were observed in terms of pop-outs and scaling throughout the various mixes (as shown in Figure 10), including the control, no worthy deterioration was noted overall in the slabs. Though it is noted that RCA mixes displayed a somewhat higher occurrence of pop-outs, less surface deteriorations and cracks were seen relative to the control. All mixes were observed to have withstood the freeze-thaw cycles and salting trips well with only small deteriorations.

Figure 10: Minor pop-out (left) and scaling (right) occurrence in mixes

Figure 11: Site Condition – 30% Coarse (1 Year)

Figure 12: Site Condition – Control Mix (1 Year)

Figure 13: Site Condition – 20% Granular Mix (1 Year)

8 Conclusions

This field trial paves the way for broader acceptance in the use of RCA in concrete production. Mixes incorporating coarse and granular RCA displayed acceptable performance in terms of fresh, hardened, and durability properties measured in this research program. It was possible to produce robust RCA mixtures that satisfy the CSA criteria for class C-2. Five industrial classes of RCA mixtures with adequate performance were successfully developed. These mixtures can cover various ranges of applications, such as pavements, sidewalks, garage floors, curbs, and gutters. The following observations were made based on field-trial performance of RCA containing concrete placed as a sidewalk:

- Equivalent compressive strength development was observed in mixes containing coarse-graded RCA up to 30% and granular graded RCA up to 20%, satisfying the criteria of Class C-2 mixtures as per CSA A23.1.
- A relatively minimal decrease in flexural strength (approx. 10%) was observed for mixes incorporating RCA. Gradation was found not to be an influential factor.
- No significant or noticeable damage occurred for freeze-thaw, regardless of RCA gradation or replacement level. Coupled with the AVS results, it is interpreted that the air void system is sufficient to accommodate freeze-thaw cycles, without detrimental damage occurring to the concrete.
- At the end of 50 cycles, the visual ratings for salt surface scaling resistance observed similar performance for the control and coarse RCA mixes. Slight scaling was observed for mixes made with the 20-0mm RCA mix.
- No significant impact was observed for the fresh properties of all mixes. It was thought that the workability of the 20-0mm RCA mix would have been negatively impacted, due to the high absorption of ultra-fines present in the full graded 20-0mm RCA. However, the contractor was impressed with the smoothness and improved finish-ability of this mix due to increased fines, thus it was not an issue for this application.

- An analysis of the air void system showed that the 20-0mm concrete mix had the lowest hardened air voids, in line with the control. The inherent porosity of the mortar phase in the recycled coarse aggregate is believed to have contributed to the higher hardened air voids.
- Rapid chloride permeability tests at 56 days displayed equivalent levels of performance, regardless of RCA replacement level due to the contribution of the slag in the mix to densify the paste matrix. Only marginal reductions in resistance to chloride penetrability were observed in RCA mixes, contributable to the lowered density of the RCA.
- The RCA mixes showed equivalent workability to the control mixes during construction. The contractor noted a consistency between all the mixes.
- After one year, the sidewalk slabs displayed only minor defects. The RCA mixes showed an equivalent or improved durability performance to the control. However, more pop-outs were noticed in the RCA mixes over the control. Overall, no major deterioration was observed after the initial winter.

This trial demonstration proves the use of RCA in air entrained concrete mixes is technically feasible when used in low replacement percentages up to 30% coarse and 20% overall aggregate volume. This practice allows for concrete to be more sustainable and reducing the need for virgin aggregates and extending this mineral resource.

Developed RCA mixtures incorporating recycled aggregates have great potential to be used in practical construction applications. The use of such materials can lead to sustainable construction through reduction in the use of virgin aggregates, reduction of waste streams and cost savings.

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