Properties of Concrete Containing Recycled Concrete Aggregate of Preserved Quality

Jonathan Andal[a], Medhat Shehata[a*], Philip Zacarias[b]

[a]Ryerson University, 350 Victoria St, Toronto, ON, Canada
[b]St Marys / Canada Building Materials, Toronto, ON, Canada

Abstract

This study focuses on evaluating recycled concrete aggregate (RCA) of high quality produced through a protocol that preserves the original properties of the concrete to be recycled. Concrete with RCA of preserved quality was compared to concrete with commercially available RCA. A total of 29 mixes were tested with RCA replacement ranging from 30% to 100% of the coarse aggregate. Results showed that concrete with RCA of preserved quality performed significantly better in compressive strength, drying shrinkage, and salt scaling resistance. Furthermore, the use of 30% RCA with preserved quality produced concrete of comparable quality to that of concrete with natural aggregate.

Keywords: recycled concrete aggregate, salt scaling, shrinkage, strength, permeability

* Corresponding author: Tel.: +1 416 979 5000 ext. 6457
E-mail address: mshehata@ryerson.ca (M.Shehata)

1. Introduction

The depletion of virgin aggregate sources has become a widespread issue. This has brought forth a need for an alternate aggregate source. In recent years, research into recycling concrete has gained considerable attention. Through continuous cycles of rehabilitation, renovation, and demolition, there has been an accumulation of concrete waste. Concrete wastes can also be generated from concrete that is returned from job sites to batching plants due to a number of reasons, including not meeting requirements or being in excess of what was needed. This type of RCA, known as returned-to-plant RCA, is discharged from the transit mixer and left to harden. The hardened concrete is crushed and processed to produce RCA. Currently, RCA use has been limited to granular backfill, subgrade material, and sidewalk concrete [1]. While sustainability and economic reasons have continued to push research into RCA forward, factors related to quality assurance and quality control have hindered its use in field applications [2]. The main difference between RCA and virgin aggregate is the residual mortar that surrounds the original stone in RCA. The residual mortar can affect the fresh, hardened, and durability properties of concrete incorporating RCA.

The physical properties of coarse RCA are quite different to virgin aggregate. RCA usually have a rougher texture and more angular shape. Additionally, RCA tend to have a lower specific gravity and bulk relative density while having a higher absorption and porosity [3]. RCA is associated with high absorptive properties due to the presence of the residual mortar. When dry RCA is used in mix designs without correcting for absorption, it lowers the effective water cement ratio and results in a higher compressive strength [4] and lower workability. The residual mortar in RCA also affects its mechanical properties making it of higher abrasion and crushing value compared to virgin aggregate [5].

RCA also has an effect on the fresh properties of concrete. The greater angularity, surface roughness, absorption and porosity contribute to the decrease in workability of fresh RCA concrete. The rapid loss in workability can be attributed to the increase in fines during the mixing process. As the mixing drum continues to rotate the residual mortar in RCA can be broken down or chipped away to create more fines [6]. An interfacial transition zone (ITZ) exists in concrete consisting of virgin aggregate which is known as a weak plane within the matrix of the concrete. This zone contains a slightly higher water-to-cement ratio (w/c) than the rest of the concrete [7]. Concrete incorporating RCA has two ITZs: one between the original aggregate and the residual mortar and one between the RCA and the fresh paste [8]. A two stage mixing approach (TSMA) has been used to improve the ITZ between RCA and the new cement paste. The TSMA, developed by Tam, Gao and Tam [9] divided the mixing process into two stages where half the mixing water is mixed first with the aggregates, and the second half is added after with the rest of the ingredients. This method enables overcoming the porous property of RCA and produces a denser concrete matrix [10].

The compressive strength of RCA concrete is typically lower than concrete with virgin aggregate. Hansen [11] suggested that the compressive strength of RCA concrete could decrease up to 25% depending on the quality of RCA. Kwan et al. [12] stated that an increase in the amount of coarse RCA used as a replacement to virgin aggregate led to a decrease in compressive strength. This decrease in strength was attributed to the low strength of the residual mortar in RCA. Salau et al. [13] confirmed this trend and stated that it was attributed to lower specific gravity and high absorption or porosity of RCA. They also stated that the strength of RCA concrete was governed by the weaker of the two interfaces between the residual mortar and the original stone and between the residual mortar and the new mortar. McNeil [14] stated that the compressive strength is affected by several factors including the water/cement ratio, the percentage of coarse aggregate replaced with RCA, and the amount of residual mortar in the RCA.

Many studies have reported that concrete with RCA experiences greater shrinkage than concrete with virgin aggregate [15]. Shrinkage is affected by a number of factors, including cement type and quantity, water/cement ratio, aggregate type and quantity, size of the specimen, and the relative humidity of the environment [16]. Guo et al. [15] and Faithifazal et al. [2] suggested that an increase in coarse RCA replacement also increased shrinkage. They stated that this increased shrinkage was due to the higher porosity of RCA compared to virgin aggregate. A Missouri University study [17] reported an increase in shrinkage in RCA concrete where concrete incorporating 70% coarse RCA replacement exhibited approximately 25% more shrinkage compared to the control samples. The authors of the report attributed the increase in shrinkage to lower stiffness and restraining capacity of RCA. Domingo et al. [4] experienced a 12% increase in drying shrinkage with a 50% RCA replacement. Salau et al. [13] reported a 36% increase in shrinkage with a RCA replacement of 25%. Hansen [11] stated that concrete incorporating coarse RCA and natural sand exhibited 50% more drying shrinkage compared to concrete with natural coarse aggregate and natural sand. In general, earlier studies have shown shrinkage to be higher in concrete with RCA; however, the increase in shrinkage varied from one study to another, likely due to different quality of RCA.

Impurities or contamination of coarse RCA can lead to loss of resistance to chemical attack [18] or alkali-aggregate reaction (AAR) if the RCA is produced from structures affected by AAR [19]. In addition, the porous nature of RCA makes RCA-concrete prone to frost damage [20]. Hwang et al. [21] showed that samples containing 100% RCA and 60% GGBFS exhibited a mass change of approximately 9% while the 100% RCA-samples exhibited a mass loss of 17% after 300 freeze-thaw cycles. Huda and Alam [22] reported that after 300 freeze-thaw cycles, a 50% replacement of RCA lead to a length change of 0.09% while the control specimen exhibited a length change of approximately 0.075%. In terms of salt scaling, Jain et al. [23] reported that samples incorporating 100% RCA and Type C fly ash were able to achieve a satisfactory performance after 50 cycles of exposure. They stated that the RCA samples experienced scaling comparable to the control specimen. They attributed the resistance to scaling to an efficient air void system in the concrete mixture

The objective of this research was to adopt a protocol to produce RCA of preserved quality, and investigate whether or not concrete mixtures incorporating the produced RCA have better properties compared to concrete containing commercially available returned-to-plant RCA. Following the adopted protocol, the returned concrete is separated based on strength where concrete of strength of 25 MPa or higher is separated and used to produce the RCA investigated in this study. More importantly, the protocol involves controlling and minimizing the amount of water used to discharge the returned concrete from the transit mixer in order to preserve the original quality of the concrete. To evaluate the RCA produced using the protocol, concrete containing virgin natural aggregates, concrete with commercial RCA, and concrete with preserved-quality RCA were investigated using a number of strength and durability tests.

2. Materials and Experimental Details

2.1 Materials

2.1.1 Aggregates

Two types of RCAs were used in this study, referred to as RCA with preserved quality (or preserved-quality RCA) and commercial RCA. Both types are classified as coarse RCA with maximum nominal size of 20 mm. The preserved-quality RCA was produced following a protocol that aimed at maintaining or preserving the quality of the original concrete. The protocol of producing the preserved-quality RCA focused on: (a) separating the returned concrete based on its grade or strength where only 25 MPa-concrete or higher is used; and (b) controlling and minimizing the addition of water while discharging the returned concrete from the transit mixer. Conversely, the other type of RCA used for comparison purposes was mainly a returned-to-plant commercial RCA that may contain some recycled old concrete rubbles with a maximum of 1% deleterious material, such as wood or asphalt. Figure 1 shows a picture of preserved-quality RCA, and Figure 2 shows a close-up of the same materials. Figure 3 shows a close-up of the commercial RCA. The presence of original stone as well as residual mortar can be seen on both types of RCAs.

In addition to RCA, coarse natural limestone virgin aggregate, Dolostone, and natural fine sand were used in the study. The Dolostone was quarried in Hamilton, Ontario, Canada and is used in commercial concrete in Ontario. The natural sand was from Caledon, Ontario and is considered high quality concrete sand. Coarse and fine natural aggregates were in compliance with the gradation and other requirements of the Canadian Standards CSA A23.1 [24].

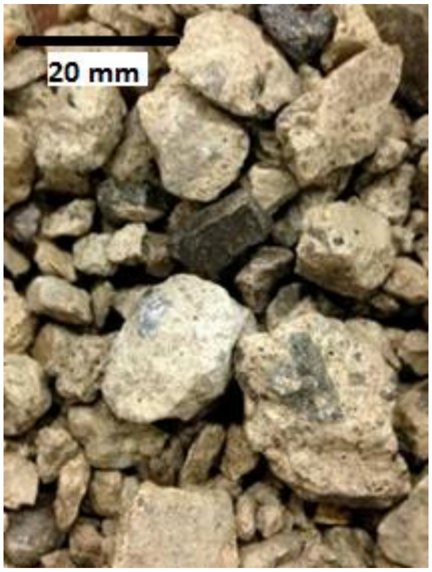


Figure 1: Sample of RCA with preserved quality produced in this study

Figure 2: A close-up of the preserved-quality RCA produced in this study

Figure 3: A close-up of the commercial RCA used in this study

2.1.2 Cementing Materials

General use (Type GU) Portland cement was used in all mixtures. Ground Granulated Blast Furnace Slag (GGBFS) was used in some mixtures as a supplementary cementing material to replace a percentage of Portland cement. The chemical analysis of the cementing materials is listed in Table 1.

Table 1: Chemical analysis of the cementing materials

Cementing Material	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	TiO_2 (%)	P_2O_5 (%)
Portland Cement (GU)	62.61	19.33	5.25	2.42	2.35	4.03	0.28	0.13
GGBFS	39.9	36.9	7.82	0.68	11.2	0.45	0.41	-

2.2 Concrete Mixtures

A total of 29 concrete mixtures were cast and tested as identified in Table 2. The mixture proportions, water-to-cementing materials ratio (w/cm), and air content for each mix are listed in Table 3. These mixes are designed to meet three classifications; C2, F1 as per Canadian Standards [25] and a relatively low strength concrete mix, 15 MPa. The Classes of Exposures C2 and F1 are described in Table 2.

Table 2: Identification and description of the mixtures used in this study

Mix identification	Description
CON	Control mixture containing natural Dolostone – No RCA
R	Preserved-quality RCA
RUC	Commercial RCA
30R, 50R* or 100R	Mixtures with 30, 50 or 100% preserved-quality RCA (R) replacement by mass of coarse aggregate.
30RUC, 50RUC* or 100RUC	Mixtures with 30, 50 or 100% commercial RCA (RUC) replacement by mass of coarse aggregate
15S or 30S	Mixtures with 15 or 30% GGBFS replacement by mass of total cementing materials .
15 MPa	15 MPa concrete - air-entrained: can be used in an applications that do not require high strength and can be exposed to freezing and thawing.
C2	Exposure class C2 as per CSA A23.1-2014: Non-structurally reinforced concrete exposed to chlorides and freezing and thawing: a maximum w/cm of 0.45, a minimum compressive strength of 32 MPa after 28 days and an air content of 5-8%.
F1	Exposure class F1 as per CSA A23.1-2014 : Concrete exposed to freezing and thawing in a saturated condition but not to chlorides: a maximum w/cm of 0.50, a minimum compressive strength of 30 MPa after 28 days and air content of 5-8%

*All C2 samples were tested for salt scaling with the exception of 50R and 50RUC

Table 3: Proportions of the investigated concrete mixtures

Mix	Portland Cement (Kg/m^3)	GGBFS (Kg/m^3)	Dolostone (Kg/m^3)	RCA[1] (R) (Kg/m^3)	RCA[2] (RUC) (Kg/m^3)	Natural Sand (Kg/m^3)	Water (Kg/m^3)	w/cm	Air (%)
15-CON	250	-	1058	-	-	836	155	0.62	5.0
15-30 R	250	-	688	295	-	865	155	0.62	5.2
15-100R	250	-	-	877		866	155	0.62	5.8
15-CON-30S	175	75	1058	-	-	832	155	0.62	5.2
15-30R-30S	175	75	688	295	-	861	155	0.62	4.6
15-100R-30S	175	75	-	877	-	862	155	0.62	6.0
C2-CON	335	-	1058	-	-	737	151	0.45	5.2
C2-30R	335	-	688	295		766	151	0.45	5.6
C2-50R	335	-	507	507	-	752	151	0.45	6.6
C2-100R	335	-	-	908	-	731	151	0.45	5.8
C2-CON-30S	235	100	1058	-	-	731	151	0.45	6.2
C2-30R-30S	235	100	688	295	-	760	151	0.45	6.0
C2-100R-30S	235	100	-	908	-	725	151	0.45	6.6
C2-30RUC	335	-	696	-	298	754	151	0.45	6.4
C2-50RUC	335	-	508	-	508	746	151	0.45	6.2
C2-100RUC	335	-	-	-	911	722	151	0.45	7.2
C2-30RUC-30S	235	100	696	-	298	748	151	0.45	6.0
C2-100RUC-30S	235	100	-	-	911	716	151	0.45	6.2
F1-CON	332	-	1058	-	-	687	166	0.50	5.8
F1-30R	332	-	688	295	-	715	166	0.50	6.0
F1-100R	332	-	-	908	-	681	166	0.50	6.0
F1-CON-30S	232	100	1058	-	-	681	166	0.5	5.4
F1-30R-30S	232	100	688	295	-	708	166	0.5	5.4
F1-100R-30S	232	100	-	908	-	675	166	0.5	6.8
C2-CON-15S*	285	50.3	1058	-	-	734	151	0.45	5.6
C2-30R-15S*	285	50.3	688	295	-	762	151	0.45	5.6
C2-100R-15S*	285	50.3	-	908	-	728	151	0.45	6.2
C2-30RUC-15S-*	285	50.3	696	-	298	752	151	0.45	6.6
C2-100RUC-15*	285	50.3	-	-	911	718	151	0.45	7.0

[1]: Preserved-quality RCA: R
[2]: Commercial RCA: RUC
*: these samples were tested for resistance to salt scaling

2.3 Experimental Details

2.3.1 Aggregate Testing

To compare the properties of the commercial and preserved-quality RCA, both materials were tested for gradation as per ASTM C136 [26], micro-deval abrasion as per ASTM D6928 [27], absorption and bulk relative density as per ASTM C127 [28] and ASTM C128 [29], and dry rodded density as per ASTM C29 [30].

In addition, the residual mortar content in both RCA was determined following the procedure described by Abbas et al. [31], except that the test was extended to ten cycles instead of five. In this residual mortar content test, representative samples from the preserved-quality and commercial RCA were obtained from which 1000 g of the 9.5-4.75 mm fraction and 2000 g of 19.5-9.5 mm fraction were obtained. Three samples from each size were collected and tested. Asphalt or any foreign materials were removed from the commercial RCA to make sure that only recycled concrete particles were tested. The coarse RCA was washed on 4.75-mm sieve for size 4.75 mm to 9.50 mm, and on 9.5 mm-sieve for size 9.5 mm to 19.5, followed by drying for 24 hours at 105°C. The oven-dried aggregate samples are then immersed in a 26% by weight sodium sulfate solution for 24 hours. Then the RCAs were subjected, while in their solution, to 10 cycles of freezing and thawing; each cycle consists of 16 hours at -17°C followed by 8 hours at 80°C. After the first five freezing and thawing cycles, the solution was drained from the samples and the RCAs were washed over a sieve of one size smaller than the sample size; i.e., 4.75 mm for particle size 9.5 mm to 19.5 mm, and sieve 2.36 mm for particle size 4.75 mm to 9.5 mm. After that, the samples were dried at 105°C and their dry masses W_o were determined. The mass loss after 5 cycles was determined using the following equation:

$$Mass\ Loss\ = \frac{(W_{RCA} - W_O)}{W_{RCA}} * 100$$

On inspecting the samples after five cycles, it was determined that the RCA particle still had adhered mortar. It was decided at that time to run the test for additional five cycles and determine the mass loss after the ten cycles. This mass loss was taken as the residual mortar content, as it was found by visual inspection that most of the adhered mortar were lost during the ten cycles.

2.3.2 Concrete Testing:

2.3.2.1 Mixing

A two-stage mixing procedure was followed for all mixtures tested in the study. The mixing procedure is listed in Table 4.

Table 4: Concrete Mixing procedure

Step	Materials/procedure	Mix duration (seconds)
1	Coarse and fine aggregate (including AEA)	60
2	Rest	60
3	First half of the mixing water	60
4	Rest	60
5	Cementing material (including GGBFS if needed)	30
6	Second half of the mix water (including WRA)	120
7	Rest	120
8	Mix	120
9	Rest	120

2.3.2.2 Fresh Properties:

Air content was carried out on fresh concrete following ASTM C231 [32]. Slump testing was performed according to CSA A23.2-5C or ASTM C143 [33]. To examine slump retention, slump test was carried at 15-minute intervals for a total of 45 minutes. During this time, the concrete was kept in the mixer covered by wet burlap to prevent water evaporation.

2.3.2.3 Mechanical Testing

Compressive strength test was performed according to ASTM C39 [34] using 100 x 200 mm cylinders with ground ends at 7 and 28 days. All results were recorded and presented as an average of three test specimens. Compressive strength testing was performed on all three classes of concrete: C2, F1 and 15 MPa. A comparison between the commercial RCA and RCA of preserved quality was carried out using C2 concrete. Splitting tensile strength test was performed according to ASTM C496 [35] using 100 x 200 mm cylinders at 28 days. The results are recorded and presented as an average of three test specimens. Only C2 concrete samples were tested for splitting tensile strength.

2.3.3.3 Durability Testing

Drying shrinkage was performed according to ASTM C157 [36] on 75 x 75 x 285 mm concrete specimens for 180 days. Demoulding and curing were carried out following the Ready Mixed Concrete Association of Ontario (RMCAO) method. In this method, the concrete samples were cured in lime-saturated water for 7 days. After curing was complete, the initial reading of each specimen was taken using a length comparator, prior to being placed in the shrinkage room. Drying shrinkage was carried out at 50 $\pm$ 4% relative humidity and temperature of 23 $\pm$ 2°C. All subsequent shrinkage readings were referenced to the initial reading taken before the samples were exposed to the drying conditions. All results were reported as an average and standard deviation of three test specimens. Only C2 mixtures were tested for drying shrinkage. Additionally, two sets of C2 samples were cast at a later date to verify the obtained results. These samples were from the same batched concrete cast at Ryerson University. One set of three specimens (one sample) was stored and tested at Ryerson and the other set was stored and tested at an external facility. Both commercial RCA and RCA of preserved quality were tested at Ryerson and at the external facility.

Salt scaling testing was performed according to the Ministry of Transportation Ontario (MTO) test method LS-412 using 300 x 300 x 75 mm slabs. Once the specimens were demoulded, they were cured for 14 days in moist storage at RH > 95%. Following the 14 days of moist storage, the specimens were stored at 23 $\pm$ 2°C and relative humidity of 45-55% for 14 days. At the end of the drying periods, the surface of each specimen was covered with approximately 6 mm of 3% NaCl solution, and then exposed to 50 freeze-thaw cycles. One cycle consisted of 16-18 hours in a freezer at -18 °C by a thawing period at 23 $\pm$ 2°C and relative humidity of 45-55% for 6-8 hours. After five cycles, the surface of each specimen was washed with the NaCl solution to collect the flaked-off concrete. The washing continued until all the loose particles were removed from the surface of the specimen, and the collected particles were dried and weighed. This was preformed every five cycles until the 50 cycles were completed. Only C2 mixtures were tested for salt scaling resistance.

The rapid chloride permeability test (RCPT) was performed according to ASTM C1202 [37] at the age of 56 days using 100 mm diameter specimens with 50 mm $\pm$ 5 thickness. These specimens were cut from the middle of 100 x 200 mm concrete cylinders. Prior to testing, specimens were placed in a vacuum desiccator and the submerged in de-aerated water for 18 $\pm$ 2 hours. The specimens were tested for a total of 6 hours. Only C2 mixtures were tested for chloride permeability. A comparison between concrete with commercial RCA and preserved-quality RCA was performed.

3. Results and Analysis

3.1 Aggregate Properties:

The grading curves for both commercial and preserved RCA are shown in Figure 4. As the figure shows, both materials have identical grading curves. The representative samples used to carry out the gradation test are the same used for all other aggregate tests reported in Table 5 and 6. The results of the residual mortar content test in Table 6 shows that both materials have similar residual or adhered mortar contents as reflected by the mass loss after 10 cycles for both materials. A one-tailed T-test was carried out to compare the results of the commercial and preserved-quality RCA to find out whether or not the residual mortar contents were significantly different. The T-tests, using a significance of 0.05, indicated that the preserved-quality RCA experienced significantly less mass loss compared to the commercial RCA after 5 cycles. After 10 cycles, however, the mass loss results were not significantly different, confirming that the residual mortar content in both RCAs were almost the same. Despite the similar residual mortar content, the micro-deval and absorption of the commercial RCA was higher than those of preserved-quality RCA, indicating a weaker mortar in commercial RCA. This is also supported by the fact that the mass loss after 5 cycles of the residual mortar test was higher in commercial RCA, suggesting faster degradation or weaker mortar.

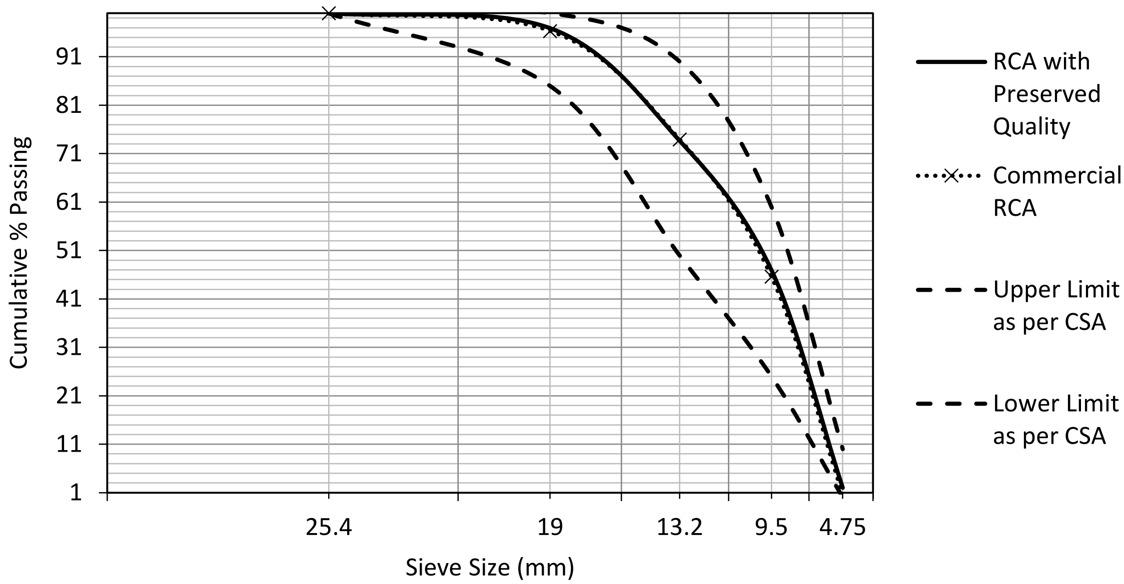


Figure 4: Gradation of the coarse commercial RCA and RCA with preserved quality – the two curves are identical

Table 5: Coarse and fine aggregate properties

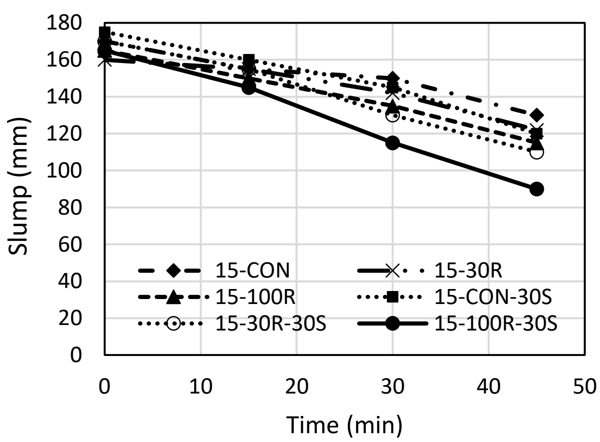
	Coarse Aggregate			**Fine Aggregate**
	Dolostone	Preserved-quality RCA	Commercial RCA	Natural sand
Absorption (%)	0.92	4.88	5.32	1.01
Bulk relative density (kg/m^3)	2720	2320	2310	2693
Dry-rodded density (kg/m^3)	1653	1418	1413	-
Micro-deval Abrasion Loss (%)	-	18.8	23.2	-

Table 6: Residual mortar test showing mass loss at 5 and 10 cycles

5 Cycles								
Preserved RCA		**Cumulative loss after 5 cycles**		**Commercial RCA**		**Cumulative loss after 5 cycles**		**P value using a significance of p = 0.05**
		% loss	**Avg.**			% loss	Avg.	
Retained 4.75 mm	R1	8.6	11.0	Retained 4.75 mm	RUC1	12.6	14.3	0.047
	R2	12.8			RUC2	15.4		
	R3	11.6			RUC3	15.0		
Retained 9.5 mm	R1	15.3	13.8	Retained 9.5 mm	RUC1	18.0	17.4	0.012
	R2	14.1			RUC2	17.1		
	R3	11.9			RUC3	17.1		
10 Cycles								
Preserved RCA		**Cumulative loss after 10 cycles**		**Commercial RCA**		**Cumulative loss after 10 cycles**		**P value using a significance of p = 0.05**
		% loss	**Avg.**			**% loss**	**Avg.**	
Retained 4.75 mm	R1	17.9	19.1	Retained 4.75 mm	RUC1	17.8	20.9	0.229
	R2	21.1			RUC2	21.4		
	R3	18.3			RUC3	22.3		
Retained 9.5 mm	R1	26.7	25.5	Retained 9.5 mm	RUC1	26.4	26.9	0.070
	R2	25.5			RUC2	27.0		
	R3	24.2			RUC3	27.2		

3.2 Fresh Properties.

The air content of the fresh concrete is presented in Table 3. Slump and slump retention testing was performed on all mixtures to evaluate the workability of RCA-concrete over time. Figure 5 shows the results for 15 MPa and F1-concrete containing preserved-quality RCA. Figure 6 compares the effect of commercial and preserved-quality RCA on workability retention of C2-concrete. In this investigation, the slump was measured at 15-minute intervals for a total of 45 minutes. As shown in Figure 5, the 15-MPa concrete with a w/cm of 0.62 achieved a high initial slump. After 45 minutes all mixtures including the RCA-concrete did not exhibit any significant slump loss, for this class of concrete. The absorptive property of the RCA had a minimal effect on reducing workability over the 45 minutes for this class of concrete with high w/cm. It should be noted that the mixing water for all concrete was corrected for aggregate absorption and that the total amount of water was added during mixing. Figure 5 also shows the slump retention of F1 concrete with a w/cm of 0.50. The concrete with virgin aggregate exhibited the highest slump after 45 minutes while the mixtures incorporating 100% RCA exhibited the lowest; however, the RCA-concrete still exhibited an acceptable slump after 45 minutes.



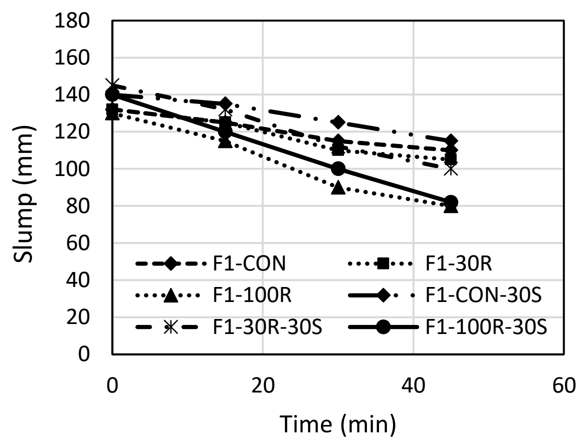


Figure 5: Slump retention of 15 MPa mixture (left) and F1 mixture (right). The RCA used in both graphs is preserved-quality RCA

Concrete of class C2 with a w/cm ratio of 0.45 were used to compare the slump retention of the commercial RCA and RCA of preserved quality. The results in Figure 6 show that the commercial RCA concrete exhibited more slump loss compared to the concrete incorporating RCA with preserved quality. This could be due to increased fines from commercial RCA during mixing since this material has lower abrasion resistance manifested by higher micro-deval loss, as listed in Table 5.

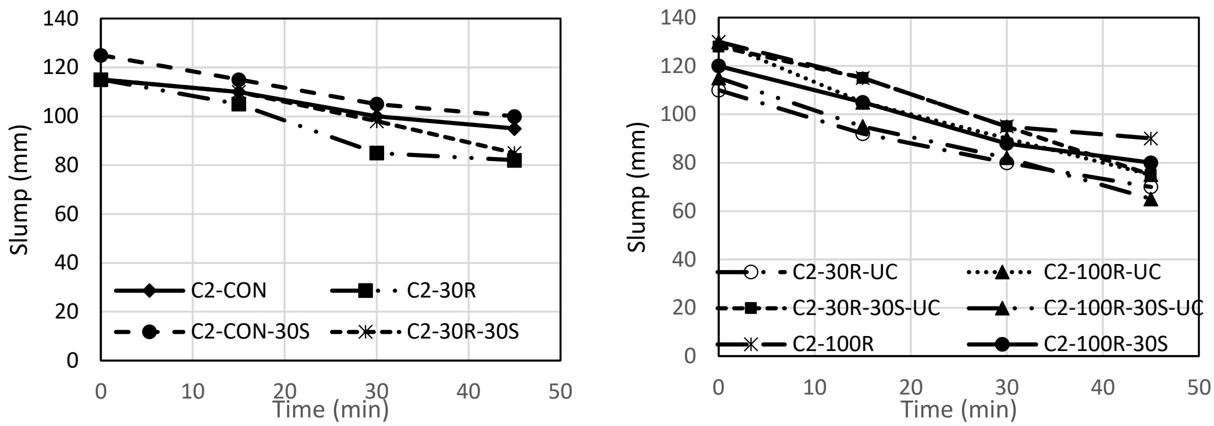


Figure 6: Slump retention of Class: C2 concrete with Preserved-quality RCA (left) and commercial RCA (right)

3.3 Compressive Strength

Compressive strength testing was performed on C2, F1 and 15-MPa concrete samples. According to CSA A23.1 [24], the minimum compressive strength requirement for C2 concrete is 32 MPa at 28 days. Table 7 shows the compressive strength results of all C2 concrete samples at 7 and 28 days along with the standard deviation between the three specimens in each sample. All samples containing RCA with preserved quality passed the CSA requirement. Two samples incorporating commercial RCA - 100UC and 100UC-30S - fell just below the required strength. Their average strengths were 31.43 and 31.87 MPa, respectively. An evident decrease in compressive strength with the increase in RCA replacement was found in all tested samples. Similar results were found by Hansen [11] as well as Limbachiya et. Al [38]. Corinaldesi [39] stated that replacing 30% of the natural coarse aggregate with coarse RCA decreased the 28-day compressive strength by approximately 20%. The decrease in compressive strength can be attributed to the low strength of the RCA or specifically the residual mortar surrounding the original aggregate in RCA.

A comparison between the effects of RCA with preserved quality and commercial RCA was performed using the results of the C2 concrete. The use of commercial RCA further decreased the compressive strength, as listed in Table 7. This can be attributed to the lower quality of residual mortar surrounding the original aggregate, as indicated by micro-deval and residual mortar tests presented earlier. The use of 30% GGBF slag showed no measurable effect on the compressive strength.

Table 7: Average compressive strength and standard deviation (SD) of C2 samples- minimum required strength after 28 days is 32 MPa – each sample consisted of 3 cylinders

	Control (natural stone)		**Commercial RCA**		**Preserved-quality RCA**	
Sample Type	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)
100% Natural Stone or 100% RCA	26.78/ 0.92	37.03/ 0.85	18.68/ 0.68	31.43/ 1.51	21.44/ 1.18	34.62/ 1.14
30% RCA			22.34/ 1.06	33.22/ 1.34	24.88/ 1.61	35.81/ 0.82
100% natural aggregate with 30% GGBFS or 100% RCA with 30% GGBFS	27.02/ 0.96	36.49/ 1.03	18.14/ 0.86	31.87/ 1.44	22.39/ 0.97	34.01/ 0.53
30% RCA with 40% GGBFS					25.48/ 0.88	36.90/ 0.97
30% RCA with 30% GGBFS			21.22/ 1.08	33.02/ 1.06		

The compressive strength results of 15-MPa and F1-concrete incorporating RCA with preserved quality, are listed in Tables 8 and 9. The samples in each category passed the 28-day requirements of 15 MPa and 30 MPa, respectively. Both classes of concrete exhibited a decrease in compressive strength with the increase in the amount of RCA replacement. While the use of 100% RCA resulted in some reduction in the strength, the use of 30% RCA as partial replacement of coarse aggregate produced compressive strength similar to that of concrete with 100% virgin coarse aggregate.

Table 8: Average compressive strength and standard deviation (SD) of 15 MPa concrete- minimum required strength after 28 days is 15 MPa – each sample consisted of 3 cylinders

	Control (natural stone)		**Preserved-quality RCA**	
Specimen Type	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)
100% Natural Stone or 100% RCA	16.40/ 0.88	24.51/ 1.12	15.34/ 0.74	21.68/ 0.69
30% RCA			16.1/ 0.64	24.11/ 0.85
100% natural aggregate with 30% GGBFS or 100% RCA with 30% GGBFS	14.85/ 0.76	22.22/ 0.70	13.08/ 0.83	18.22/ 0.82
30% RCA with 40% GGBFS			14.14/ 0.65	21.02/ 0.99

Table 9: Average compressive strength and standard deviation (SD) of F1 samples - minimum required strength at 28 days is 30 MPa – each sample consisted of 3 cylinders

	Control (natural stone)		**Preserved-quality RCA**	
Specimen Type	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)	Avg. Strength at 7 days/SD (MPa)	Avg. Strength at 28 days/SD (MPa)
100% Natural Stone or 100% RCA	25.68/ 0.99	36.02/ 0.82	22.48/ 0.42	32.12/ 0.87
30% RCA			25.08/ 0.72	33.76/ 0.56
100% natural aggregate with 30% GGBFS or 100% RCA with 30% GGBFS	25.44/ 0.97	36.02/ 0.75	19.34/ 0.54	31.61/ 0.70
30% RCA with 40% GGBFS			24.18/ 0.84	34.92/ 0.61

3.4 Splitting Tensile Strength

The splitting tensile strength testing was performed on C2 concrete at 28 days. The results are presented in Figure 7. A decrease in splitting tensile strength was apparent with the increase in the amount of RCA used as replacement. A further decrease in splitting tensile strength was observed with the introduction of commercial RCA. The decrease in splitting tensile strength was attributed to the higher porosity, lower density, and lower overall strength of the RCA. Each sample presented in Figure 7 consisted of three specimens and the variability within each sample is presented by the error bars on the graph. Tavakoli and Soroushian [40] experience similar results. They stated that the concrete strength of the original matrix (the concrete where RCA was produced from) had a significant impact on the strength of the recycled concrete when used as RCA. Furthermore, Tavaoli and Soroushian confirmed that compressive and splitting tensile strength decreased with the increased level of RCA replacement due to the presence of impurities and residual mortar. Additionally, multiple layers of interfacial transition zone (ITZ) are a contributing factor towards the reduction of splitting tensile strength [41].

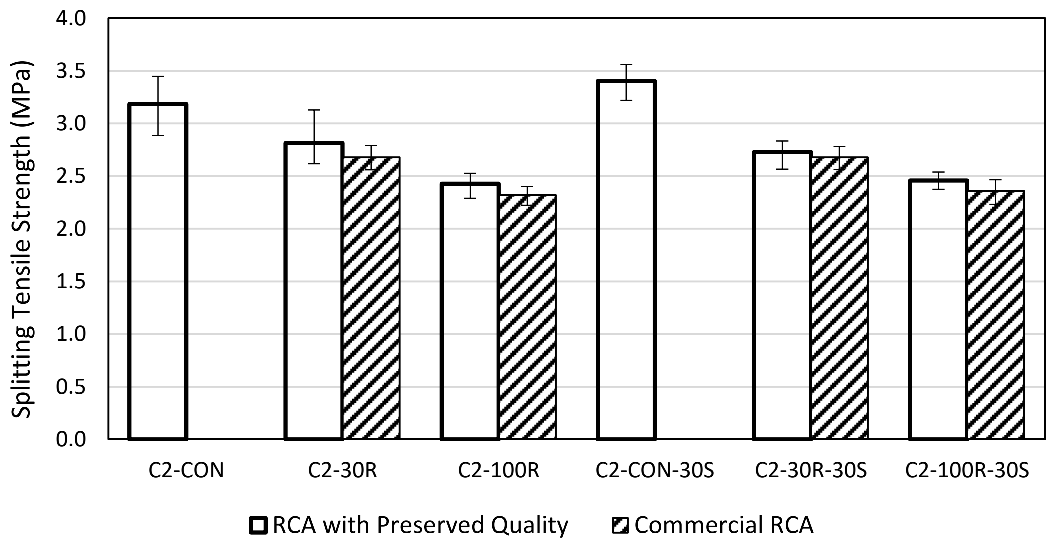


Figure 7: Splitting tensile strength of C2 concrete

3.5 Drying Shrinkage

The drying shrinkage test was performed on all C2 concrete and the results are illustrated in Figure 8; the RCA used in these samples is the preserved-quality RCA. The results indicate that the samples incorporating RCA showed more drying shrinkage compared to the control samples with virgin aggregate. At 28 days, the mixtures with 100% replacement of preserved-quality RCA experienced 40% more shrinkage compared to the control samples. At 180 days, the mixtures with 100% replacement of preserved-quality RCA experienced approximately 50% more shrinkage. The increased shrinkage is mainly due to the lower modulus of elasticity of the RCA which reduces the restraint that the aggregate exerts on the shrinking paste. The results obtained here were similar to the ones obtained by Missouri University [17] which reported 0.06% shrinkage after 200 days in samples containing 100% RCA and a water/cm ratio of 0.40. These results were based on 75 x 75 x 285 mm prisms according to ASTM C157.

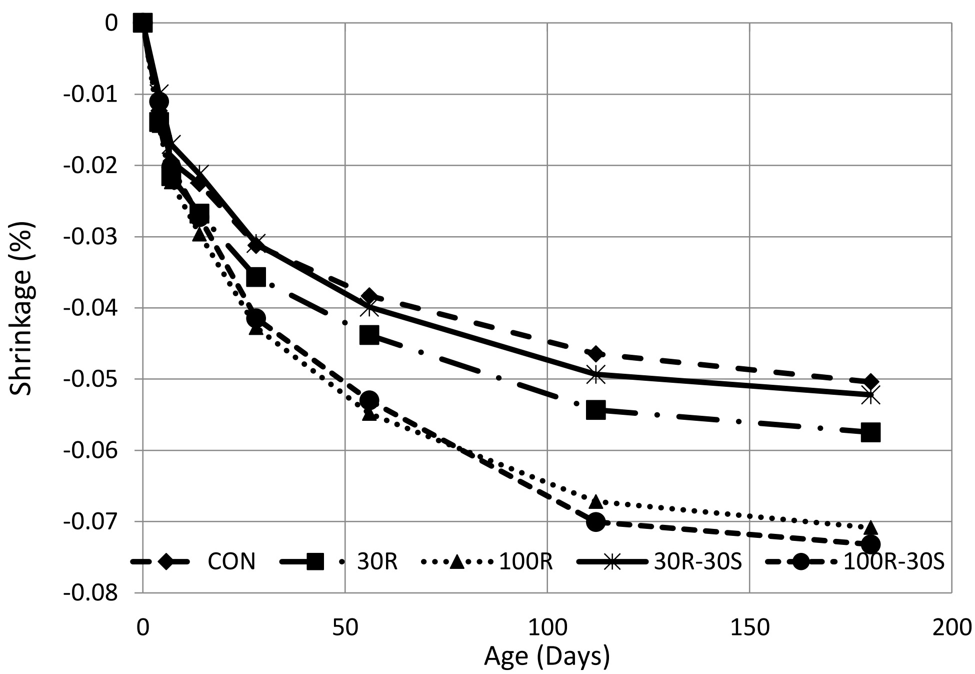


Figure 8: Drying shrinkage of C2 samples containing preserved-quality RCA

Two additional sets of C2 concrete samples were cast to compare the RCA with preserved quality and commercial RCA, and to verify the results obtained in Figure 8. The two sets were cast from the same batch to limit any variation in results. These samples were cast at Ryerson University under the same conditions. One set of three specimens (sample) was stored and tested at Ryerson University while the other set was stored and tested at an external testing facility. All samples were tested at the same period to ensure that samples with preserved-quality and commercial RCA are exposed to the same humidity and temperature throughout the testing. The results are illustrated in Figure 9 and Figure 10, which show that the results from both facilities were fairly similar. The measured shrinkage for concrete incorporating preserved-quality RCA was slightly lower than the results presented in Figure 8. This could be due to variability in the RCA sample tested or slight variability in the conditions of the testing room. At both facilities and at the age of 28 days the commercial RCA exhibited more shrinkage than the RCA of preserved quality. At 180 days, the Ryerson samples with 100% commercial RCA exhibited approximately 12% more shrinkage compared to the RCA with preserved quality. At 180 days, the 50% commercial RCA replacement exhibited approximately 12% more shrinkage compared to the RCA with preserved quality. Results obtained at the external facility showed similar results. At 180 days, the 50% and 100% commercial RCA samples exhibited approximately 7% and 10% more shrinkage compared to the RCA with preserved quality. It should be noted that each set of sample consisted of three prisms or specimens and the standard deviation within the same sample was low reflecting consistent results. Indeed, the standard deviation for the 100% RCA with preserved quality and 100% commercial RCA replacement were 0.0035% and 0.0026%, respectively. Additionally, the standard deviation for the 50% RCA with preserved quality and 50% commercial RCA replacement were 0.0010% and 0.0042, respectively.

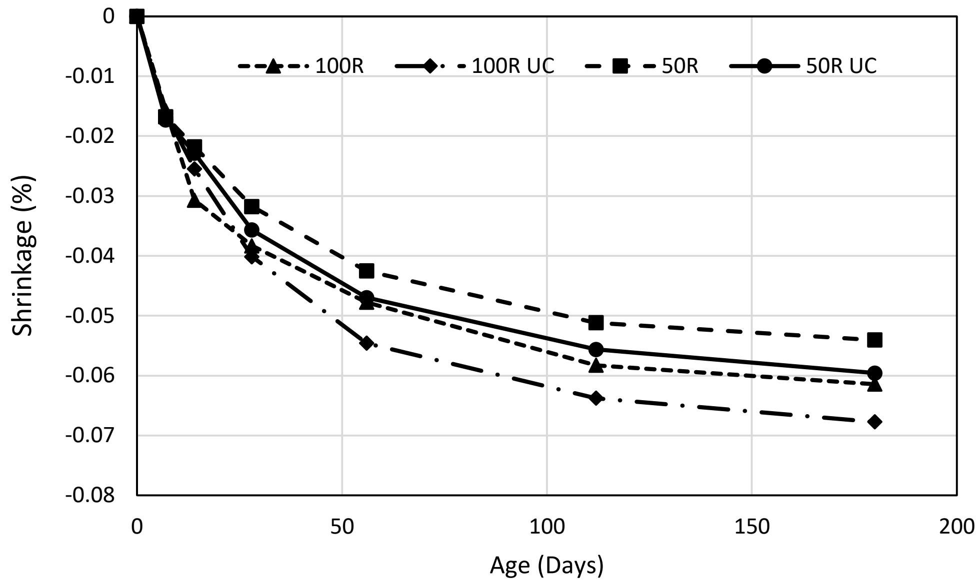


Figure 9: Drying shrinkage of C2 samples tested at Ryerson University - R refers to preserved-quality RCA and R UC refers to commercial RCA

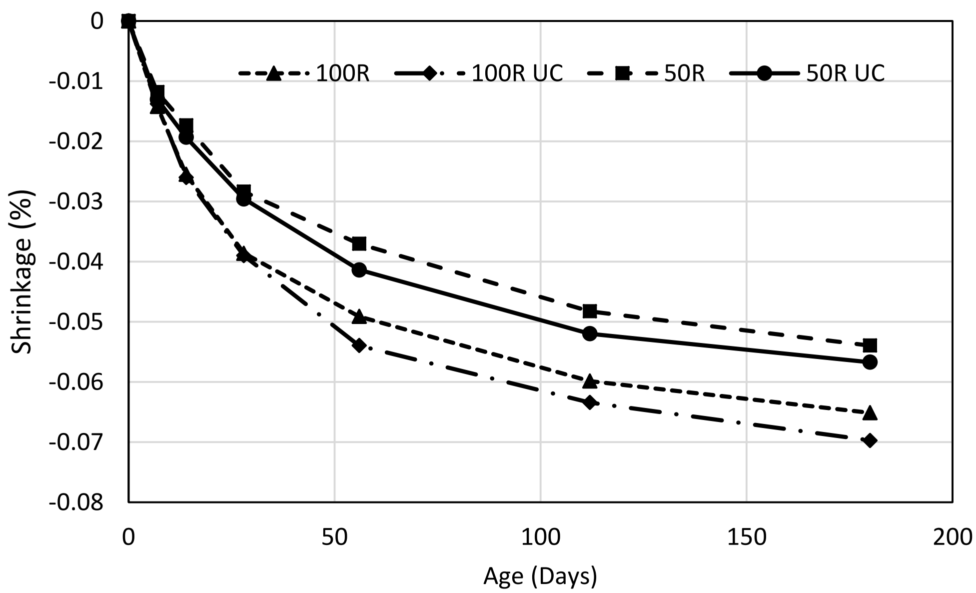


Figure 10: Drying shrinkage of C2 samples tested at an external facility. R refers to preserved-quality RCA and R UC refers to commercial RCA

3.6 Salt Scaling

Salt scaling testing was performed on all C2 concrete incorporating commercial and preserved-quality RCAs. The results are shown in Figure 11 and Figure 12, for preserved-quality and commercial RCA, respectively. The presented results are the average of 2 slabs. All samples successfully passed the Ontario Provincial Standard Specification (OPSS) of 0.8 kg/m^2 surface mass loss after 50 freeze thaw cycles. The results indicated that a 30% replacement of RCA with preserved quality had a minimal effect on salt scaling as the total mass loss was comparable to that of the control specimen with natural aggregates. The standard deviation of the sample with 30% preserved-quality RCA was 0.045 kg/m^2 and that for sample with 30% replacement of commercial RCA was 0.043 kg/m^2. The increase in the amount of RCA used also increased mass loss, but still meet the limit with a large margin of safety. It was apparent that the commercial RCA experienced the most scaling among all other samples. The results showed that a 30% replacement of commercial RCA experienced more scaling and mass loss compared to a 100% replacement of RCA with preserved quality. When comparing the 100% RCA replacement results, the 100% RCA with preserved quality achieved a standard deviation of 0.024 kg/m^2 while the 100% replacement of commercial RCA achieved a standard deviation of 0.016 kg/m^2. The standard deviation values reflected consistency between the results of the two slabs comprising each sample.

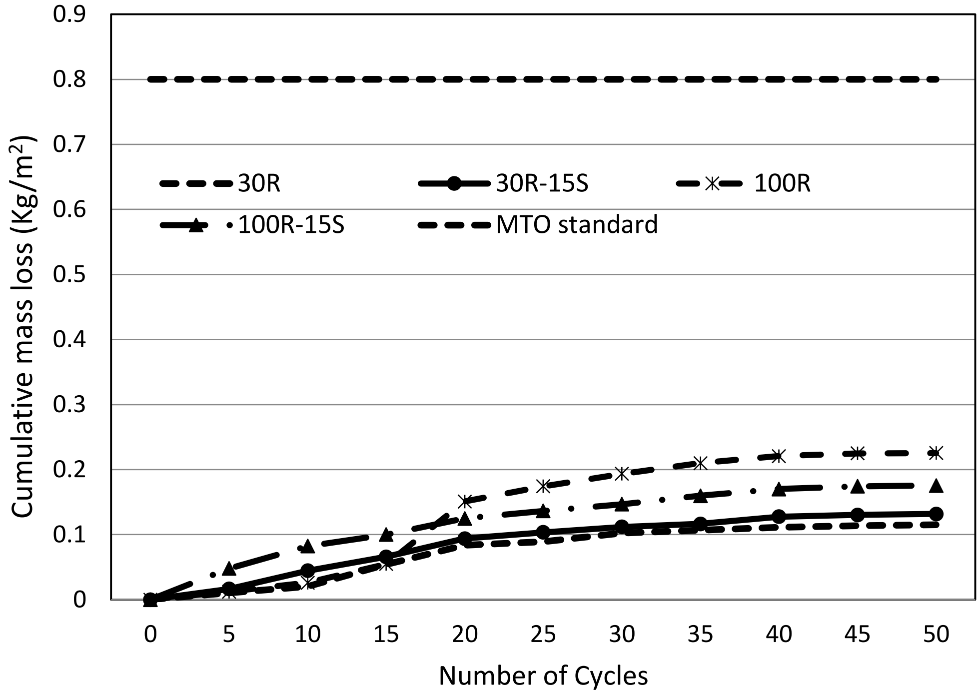


Figure 11: Salt scaling of C2 samples containing RCA with preserved quality

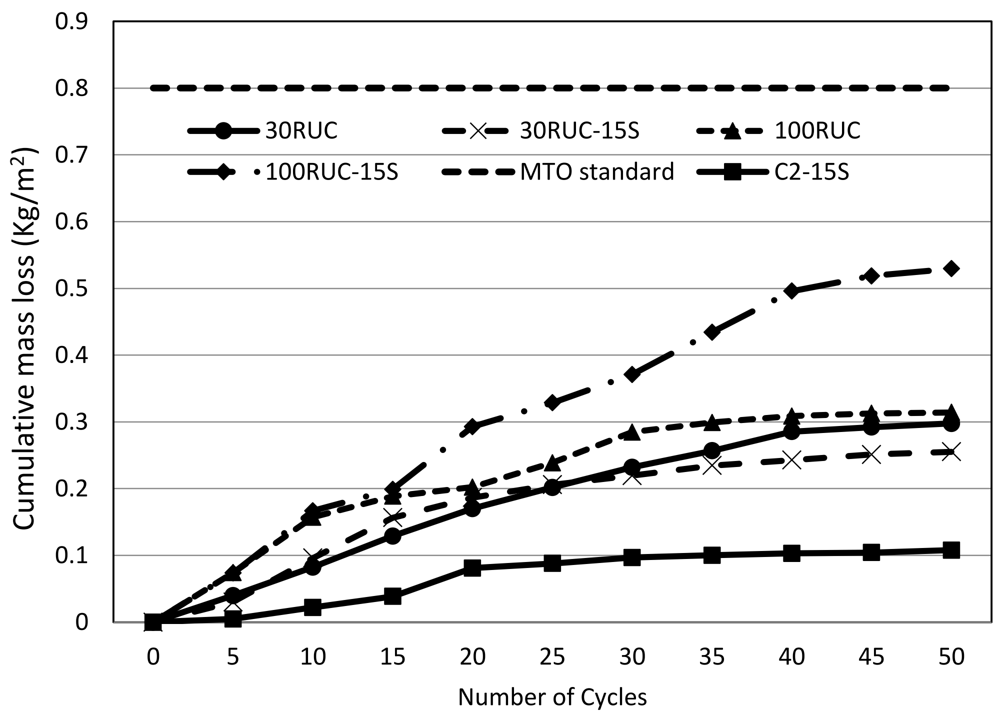


Figure 12: Salt scaling of C2 samples containing commercial RCA

Figure 13 compares the surface of concrete samples containing 100% preserved-quality RCA and 15% GGBFS to the sample containing 100% commercial RCA and 15% GGBFS after 50 cycles. It was evident through visual inspection that the slabs with commercial RCA experienced significantly more scaling. The scaling damage or mass loss was mainly in the form of aggregate pop-outs. This was particularly evident in the 100% commercial RCA slabs shown in Figure 14. The high absorptive property of RCA is thought to be one of the leading causes in the reduced durability against cycles of freezing and thawing, as the RCA particles become saturated easier and quicker compared to virgin aggregate [42].

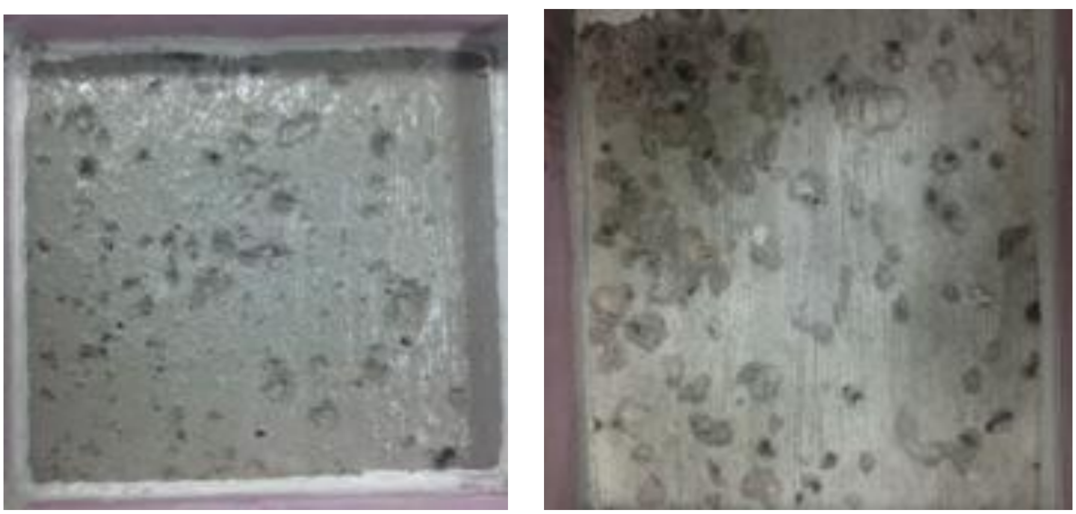


Figure 13: Concrete with 100% preserved-quality RCA and 15% GGBFS (left) and concrete with 100% commercial RCA with 15% GGBFS (right) after 50 cycles of the salt scaling test (the whole surface of the slab is shown)

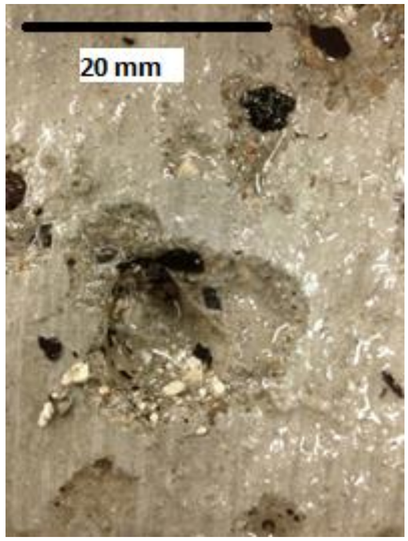


Figure 14: A Close-up of a salt scaling sample containing 100% commercial RCA

3.7 Rapid Chloride Permeability Test

Rapid chloride permeability testing was performed on all C2 mixtures at 56 days. The results, shown in Figure 15, showed that an increase in the amount of RCA used as coarse aggregate replacement increased chloride penetration. Overall, there was a further increase in chloride penetration in the mixtures with commercial RCA, but not to the extent that changes the classification of chloride penetrability. Both the 100% commercial RCA concrete and the 100% preserved-quality RCA concrete experienced moderate/high chloride ion ingression. The increase in chloride penetration with the use of RCA was attributed to the permeability of the adhered mortar. A decrease in chloride penetration was seen with the addition of 30% GGBFS, which was expected and attributable to refinement of the pore structure of the new mortar.

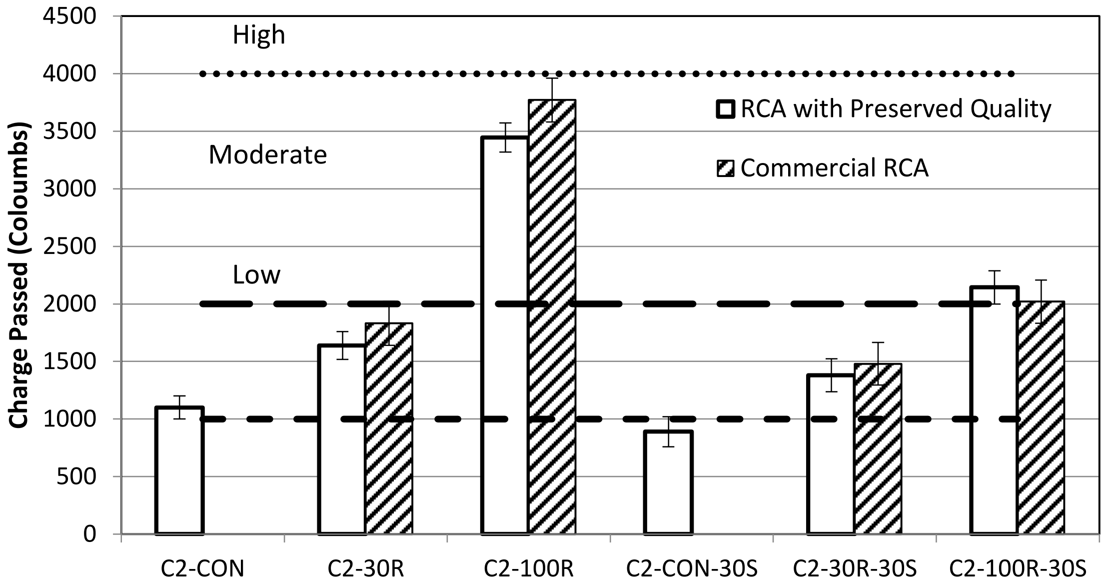


Figure 15: The rapid chloride permeability of samples at 56 days

4. Discussions

The main objective of this study was to find out if the quality of concrete containing coarse RCA can be enhanced by adopting certain procedure or protocol that aims at producing RCA of high quality. To achieve this objective, the fresh, hardened, and durability properties of concrete incorporating two types of RCA - a commercial RCA and an RCA produced using the adopted protocol - were evaluated and compared to control concrete with virgin aggregate. The preserved-quality RCA used here was produced using the adopted quality control protocol. The results and analysis have indicated that the RCA with preserved quality performed better compared to the commercial RCA in all tests. A comparison between the effects of preserved-quality RCA and commercial RCA on different properties of C2 concrete is shown in Table 10.

Table 10: A comparison of Class C2 concrete containing commercial RCA and RCA of preserved quality

Test	Virgin Aggregate	30% RCA with preserved quality	100% RCA with preserved quality	30% commercial RCA	100% commercial RCA
28-day Compressive Strength (MPa)	37.03	35.81	34.62	33.22	31.43
28-day Splitting tensile strength (MPa)	3.18	2.81	2.43	2.68	2.32
Drying shrinkage (%) at 180 days	0.050	0.057	0.061	-*	0.068
Salt scaling (Kg/m^2)	0.11	0.12	0.22	0.30	0.31
RCPT (coulombs)	1100	1640	3446	1832	3772

All data represented in Table 10 are of mixtures without GGBFS
*30% Commercial RCA was not tested for Drying shrinkage

The commercial RCA proved to produce concrete of lower strength compared to the RCA with preserved quality. This was evident since the concrete with 100% commercial RCA did not satisfy the 32 MPa requirement after 28 days. The samples containing RCA with preserved quality also experienced less drying shrinkage and less variability, which is seen in Figure 16. At a 100% replacement, concrete with commercial RCA exhibited 12% more drying shrinkage than concrete with preserved-quality RCA.

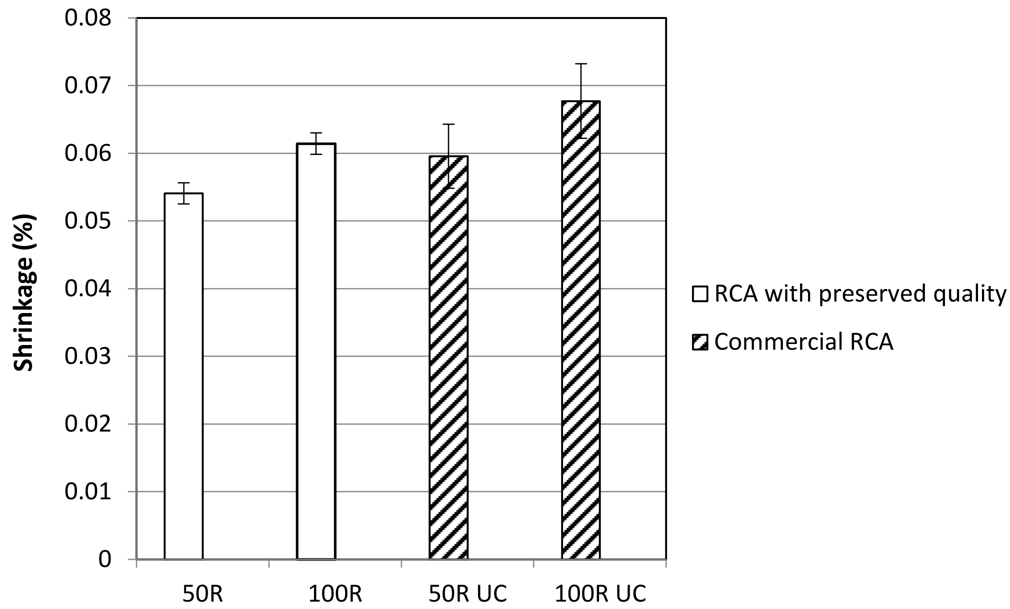


Figure 16: The shrinkage of C2 concrete containing preserved-quality and commercial RCA at 180 days at Ryerson University

Through visual inspection and the mass loss results of the salt scaling test, it was evident that concrete with commercial RCA exhibited more scaling compared to concrete containing RCA with preserved quality. Figure 17 compares the mass loss of the concrete samples containing commercial RCA to those containing RCA with preserved quality after 50 freeze-thaw cycles.

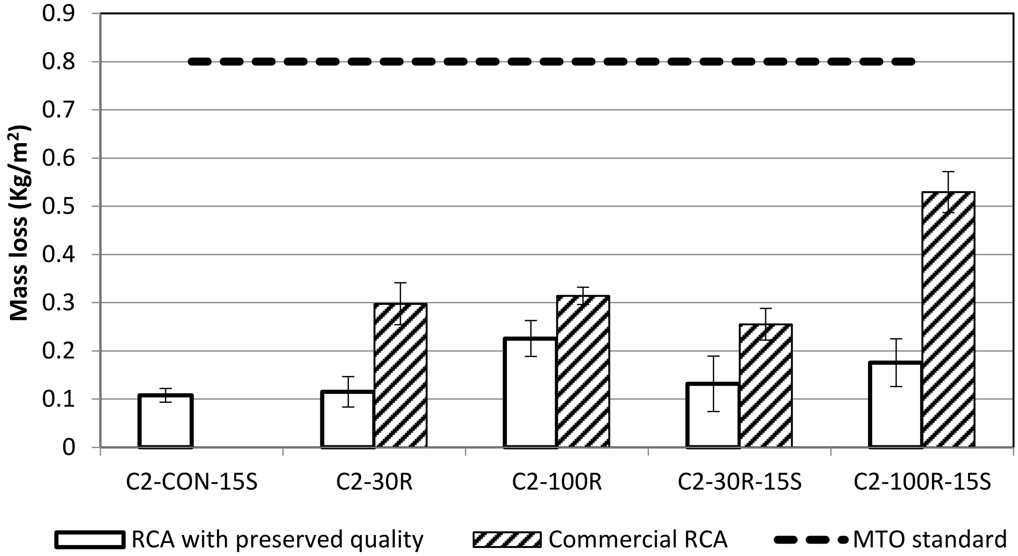


Figure 17: Mass loss of all C2 samples after 50 cycles of exposure to salt scaling test conditions

A one-tailed T-test was performed on the results obtained for both types of RCAs to confirm whether or not the difference between performance of commercial RCA and preserved-quality RCA is statistically different. The P values reported in Table 11 confirm that preserved-quality RCA produced concrete of significantly better properties compared to commercial RCA except for splitting tensile strength where the results were not significantly different.

Table 11: T-test of RCA of preserved quality Vs. Commercial RCA for various tests

	P- Value Using a significance of P=0.05			
Sample	Compressive Strength	Splitting Tensile	Drying Shrinkage	Salt Scaling
100% RCA	0.022	0.142	0.011	0.024
100% RCA with 30% GGBFS	0.036	0.083		0.016
30% RCA	0.005	0.227		0.026
30% RCA with 30% GGBFS	0.003	0.311		0.045
50% RCA			0.046	

In addition, the results showed that a 30% replacement of RCA with preserved quality produced concrete that was comparable to that produced with virgin aggregate. It is feasible to enhance the protocol used to produce RCA. For instance, separating the returned-to-plant concrete based on air-entrainment would produce RCA with an increased resistance to salt scaling.

In general, one can argue that possible reasons for the enhanced performance of preserved-quality RCA compared to commercial RCA are: (1) lower amount of adhered mortar in preserved-quality RCA compared to commercial RCA, and/or (2) mortar of better quality in preserved RCA. In terms of amount of residual mortar, the results of the residual mortar test presented in Table 6 showed no significant difference between mass loss of the two RCAs after 10 cycles. Visual inspection after 10 cycles showed both RCAs to have lost most of the residual mortar. This shows that both RCAs have similar levels of residual mortar. Hence, the enhanced performance of preserved-quality RCA is most likely due to better quality residual mortar in the preserved-quality RCA. This is justified by the lower absorption and micro-deval abrasion results of the preserved-quality RCA, listed in Table 5, despite the similar amount of residual mortar in both RCAs. More evidences of better quality mortar in preserved-quality RCA can be found by comparing the results of the adhered mortar test at 5 and 10 cycles as listed in Table 6. While the mass loss after 10 cycles for both materials are close, the loss at 5 cycles was higher for commercial RCA, suggesting that the residual mortar in this RCA broke down at a faster rate due to its lower strength. While different quality of the primary stone in RCA could have an effect on its performance, the authors believe that this is not the case here. This is because the original stone might have an effect on concrete strength, but unlikely to have significant effect on shrinkage, salt scaling or RCPT results.

While the results of the salt scaling test showed that all tested samples met the requirements for mass loss, the concrete with preserved-quality RCA had less mass loss and better appearance as shown in Figure 13. The use of 15% GGBFS did not seem to have noticeable impact on the deterioration. The main reason for the good performance of the tested concrete is that it is air-entrained. The entrained air system provided protection for the paste of the new concrete against scaling. Perhaps this is the reason why most of the deterioration was in the form of coarse aggregate (RCA) pop-out. While both adhered mortar in commercial RCA and preserved-RCA were not expected to be air-entrained, as this was not a screening criterion, polished sections of C2 concrete with both RCAs showed that they were in fact air-entrained as shown in Figures 18 and 19. However, this does not mean that all RCA particles were air-entrained; however, it indicates that worse scaling results could have been obtained if all RCA particles were non-air entrained, and perhaps better results could have been obtained if entrained air was a screening criterion for producing the RCA.

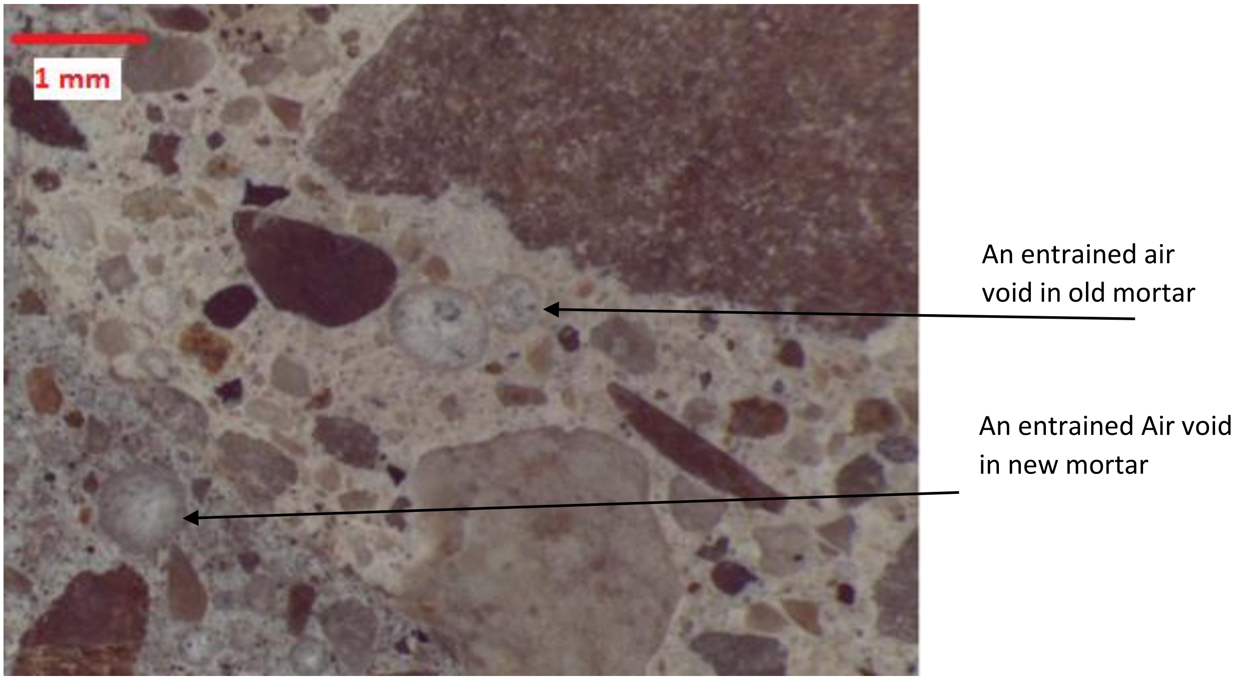


Figure 18: Polished section in C2 concrete containing preserved-quality RCA. Entrained air can be seen in the new mortar and in the residual (old) mortar of the RCA

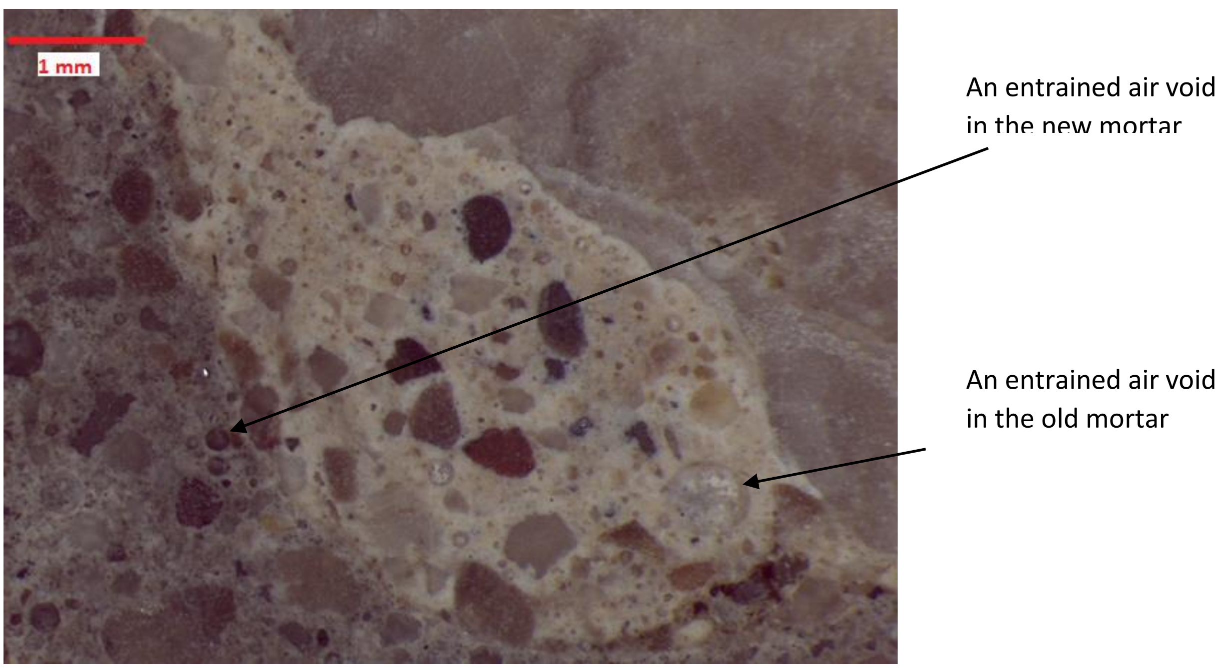


Figure 19: Polished section in C2 concrete containing commercial RCA. Entrained air can be seen in the new mortar and in the residual mortar of the RCA

The results in this paper show that a strength of 32 MPa can be obtained using commercial RCA or preserved-quality RCA which is selected based on a 25 MPa strength of the returned concrete. While the exact strength of the old concrete from which the RCAs used here was unknown, the porosity of the residual mortar indicates that the strength of the old concrete was lower than that of the C2 concrete used here. Or put another way, the w/cm of the old concrete was higher than the 0.45 used to produce C2 concrete. This can be seen in Figure 20 showing two polished sections in C2 concrete with commercial and preserved-quality RCAs. The sections were dyed by spreading few drops of methylene blue on the polished sections. In both sections, with commercial or preserved-quality RCA, a more distinct blue color can be seen in the residual mortar of RCA compared to the paste of the new concrete of 0.45 w/cm. This suggest higher porosity, or absorption, in residual mortar of both RCAs compared to the mortar of the new concrete.

No visual difference between the residual mortars in the two RCAs can be detected in Figure 20, simply because of the limitation of this methodology. Based on the observation in Figure 20, it can be stated that a higher quality RCA could be used to produce a higher strength concrete. In other words, the protocol implemented here to preserve the quality of RCA can be adopted using different or hierarchical screening criteria. For instance, RCA can be screened based on different levels of strength. This will produce RCA of different grades that can be used to produce new concrete of different strength values. Of course, screening or separating returned concrete based on air entrainment is another improvement that can be adopted to RCA production protocols.

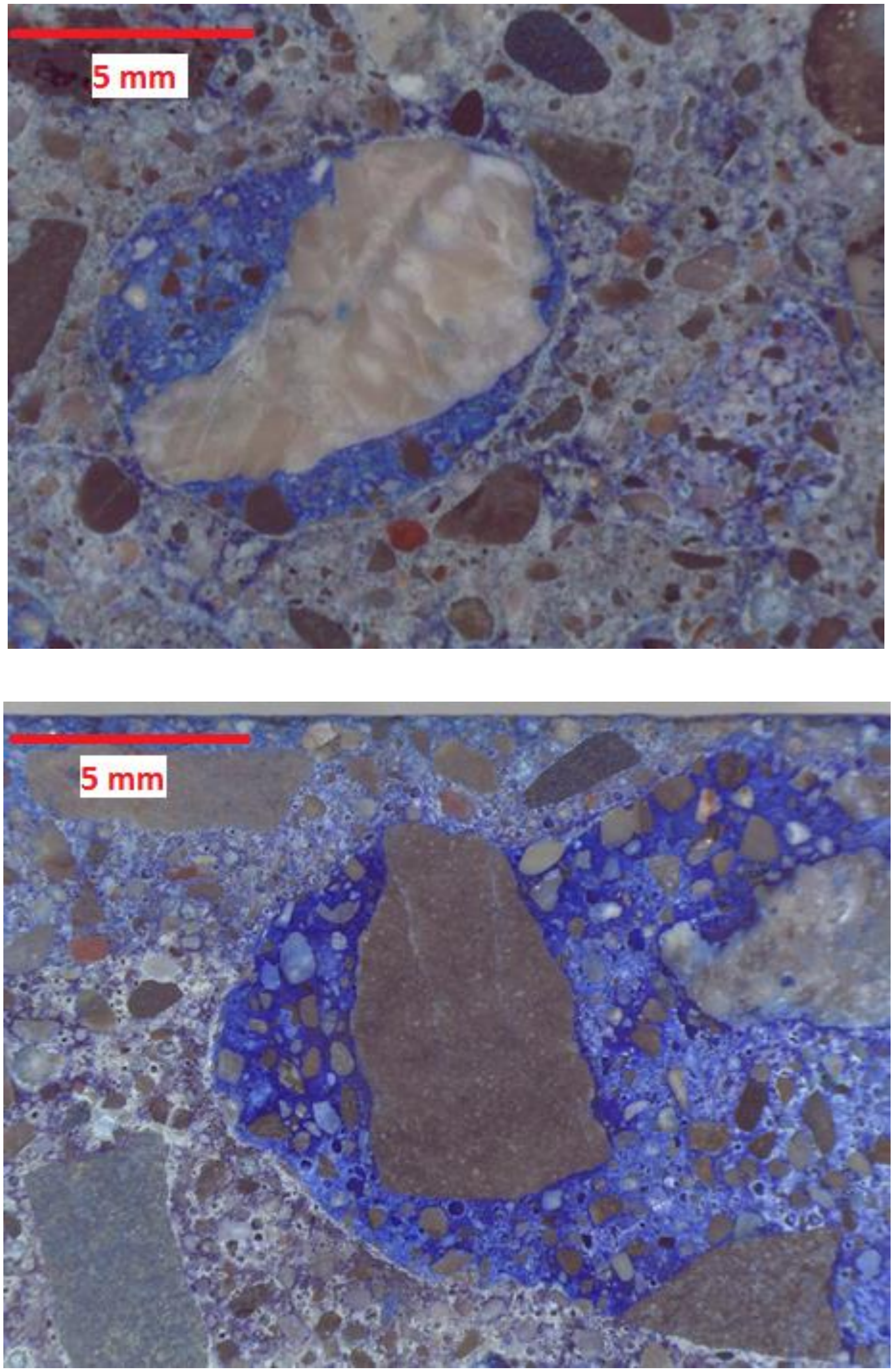


Figure 20: Polished section in C2 concrete with commercial RCA (top) and preserved quality RCA (bottom) indicated higher porosity of residual mortar in RCA compared to new paste as reflected by more absorption of the applied methylene blue dye

5. Conclusions

The following conclusions are drawn based on the findings of this study:

- An RCA production protocol that preserves the original quality of the returned concrete was adopted and found to produce RCA of higher quality than commercially available RCA. The main elements of the protocol were to separate returned concrete based on strength and eliminate or minimize the addition of water while discharging the returned concrete from the transit mixers.
- The slump retention results indicated that it is feasible to produce RCA-concrete of adequate workability and workability retention.
- Compressive strength tests indicated that an increase in the amount of RCA in the mix resulted in a decrease in compressive strength. However, concrete made with preserved-quality RCA showed higher strength when compared to the same grade of concrete containing commercial RCA. The same conclusion applies to splitting tensile strength.
- Drying shrinkage testing showed that an increase in the amount of RCA resulted in an increase in drying shrinkage. Concrete with commercial RCA experienced significantly more shrinkage compared to concrete with preserved-quality RCA. The addition of 30% GGBFS had a minimal effect on drying shrinkage.
- All salt scaling concrete samples which contained the right amount of entrained air were able to satisfy the 0.8 kg/m^2 mass loss requirement. However, an increase in the amount of RCA increased salt scaling. Concrete with commercial RCA samples exhibited significantly more mass loss compared to concrete containing preserved-quality RCA.
- Commercial RCA similar to that used in this study is best suited for use in applications with no stringent requirement for drying shrinkage and salt scaling.

- Using preserved-quality RCA at 30% partial replacement of coarse aggregate was found to produce concrete of performance similar to that of concrete with virgin aggregates.

Acknowledgment

This research project was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Engage Grant. The authors acknowledge the financial support of NSERC and the in-kind support of the industry partner St Marys / Canada Building Materials. The authors acknowledge the support of Noura Sinno, Graduate Student at Ryerson University, for her help in carrying out the residual mortar test, and Ms. Carole-Anne McDonald of the Ministry of Transportation Ontario for her help in microscopy examination.

References

[1] Butler, Liam., West, Jeffrey., Tighe, Susan. (2012). Effect of Recycled Concrete Aggregate Properties on Mixture Proportions of Structural Concrete. Transportation Research Record: Journal of the Transportation Research Board, 2290, 105-114.

[2] Fathifazl, Gholamreza., Razaqpur, A., Isgor, O., Abbas, Abdelgadir., Fournier, Benoit., Simon, Foo. (2011). Creep and drying shrinkage characteristics of concrete produced with recycled concrete aggregate. Cement & Concrete Composites, (33), 1026-1037.

[3] Sagoe-Crentsil, K. K., Brown, T., Taylor, A. H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cement and concrete research. 31(5), 707-712.

[4] Domingo-Cabo, A., Lazaro, C., Lopez-Gayarre, F., Serrano-Lopez, M.A., Serna, P., Castano-Tabares, J.O. (2009). Creep and shrinkage of recycled aggregate concrete. Construction and Building Materials, 2009, 23, 2545-2553.

[5] Chakradhara Rao, M., Bhattacharyya, S.K., Barai, S.V. (2011). Influence of Field Recycled Coarse Aggregate on Properties of Concrete. Materials and Structures, 44, 205-220.

[6] Safiuddin, M., Alengaram, U., Rahman, M., Salam, A., Jumaat, Z. (2011). Use of recycled concrete aggregate in concrete: a review. Journal of civil engineering and management, 19(6), 796-810.

[7] Scrivener, K. L., Crumbie, A. K., & Laugesen, P. (2004). The Interfacial Transition Zone (ITZ) Between Cement Paste and Aggregate. Interface Science, 12, 411-421.

[8] Ryu, J. S. (2002). Improvement on strength and impermeability of recycled concrete made from crushed concrete coarse aggregate. J. Mater. Sci. Lett., 21(20), 1565–1567.

[9] Tam, V. W., Gao, X. F., & Tam, C. M (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. Cement and concrete research, 35(6), 1195-1203.

[10] Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J., Jiang, J. (2010). Effect an mechanism of surface-coating pozzalanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete. Construction and Building Materials, 24(5), 701-708.

[11] Hansen T. Recycled aggregates and recycled aggregate concrete: second state-of-the-art report, developments 1945-1985. Materials and Structures 1986, (19), 201-246.

[12] Kwan, W. H., Ramli, M., Kam, K. J., Sulieman, M. Z. (2012). Influence of the amount of recycled coarse aggregate in concrete design and durability properties. Construction and building materials, 26(1), 565-573.

[13] Salau, M. A., Ikponmwosa, E. E., Adeyemo, A. O. (2014). Shrinkage deformation of concrete containing recycled coarse aggregate. British journal of applied science & technology, 4(12), 1791-1807.

[14] McNeil, K., Kang, T. (2013) Recycled concrete aggregates: A review. International journal of concrete structures and materials, (7), 61-69.

[15] Guo, Y., Qian, J. & Wang, X. (2013). Pore structure and influence of recycled aggregate concrete on drying shrinkage. Mathematical problems in engineering, (2013), 1-7.

[16] Boucherit, D., Kenai, S., Kadri, E. & Khatib, J.M. (2014). A simplified model for the prediction of long term concrete drying shrinkage. KSCE Journal of civil engineering, (18), 2196-2208.

[17] Missouri University. (2014). Recycled concrete aggregate (RCA) for infrastructure elements. Missouri Department of Transportation Construction and Materials, 69-72.

[18] Poon, C.S., Shui, Z.H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled concrete aggregate. Construction and building materials, 18(6), 461-468.

[19] Shehata, M. H., & Thomas, M. D. (2010). The role of alkali content of Portland cement on the expansion of concrete prisms containing reactive aggregates and supplementary cementing materials. Cement and Concrete Research , 40, 569-574.

[20] Zaharieva, R., Buyle-Bodin, F., Wirquin, E. (2004). Frost resistance of recycled aggregate concrete. Cement and concrete research, 34, 1927-1932.

[21] Hwang, J.P., Shim, H.B., Lim, S., Ann, K.Y. (2012). Enhancing the Durability Properties of Concrete Containing Recycled Aggregate by the Use of Pozzolanic Materials. KSCE Journal of Civil Engineering, 17(1), 155-163.

[22] Huda, S. & Alam, M. (2015). Mechanical and freeze-thaw durability properties of recycled aggregate concrete made with recycled coarse aggregate. American society of civil engineers, 27(10), 1-9.

[23] Jain, J., Verian, K.P., Olek, J. & Whiting, N. (2012). Durability of pavement concretes made with recycled concrete aggregates. Transportation research record: Journal of the transportation research board, 2290, 44-51.

[24] CSA 23.1. (2000). Concrete Material and Methods of Concrete Construction/Methods of Test for Concrete. Toronto: Canadian Standards Association.

[25] Canadian Standards Association. (2009). Concrete materials and methods of concrete construction/Test methods and standard practices for concrete. Canadian Standards Association. CSA.

[26] ASTM C136. (2014). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. West Conshohocken, PA, DOI: 10.1520/C0136_C0136M-14.

[27] ASTM D6928. (2010). Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. West Conshohocken, PA, DOI: 10.1520/D6928-10.

[28] ASTM C127. (2015). Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. West Conshohocken, PA, DOI: 10.1520/C0127-15.

[29] ASTM C128. (2015) Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. West Conshohocken, PA, DOI: 10.1520/C0127-15.

[30] ASTM C29. (2009). Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate. West Conshohocken, PA, DOI: 10.1520/C0029_C0029M-09.

[31] Abbas A, Fathifazl G, Isgor OB, Razaqpur AG, Fournier B, Foo S. (2007) Proposed method for determining the residual mortar content of recycled concrete aggregates, J ASTM Int. 2007, 5(1).

[32] ASTM C231. (2014). Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. West Conshohocken, PA, DOI: 10.1520/C0231_C0231M-14.

[33] ASTM C143. (2015). Standard Test Method for Slump of Hydraulic-Cement Concrete. West Conshohocken, PA, DOI: 10.1520/C0143_C0143M-15.

[34] ASTM C39. (2015). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. West Conshohocken, PA, DOI: 10.1520/C0039_C0039M-15A.

[35] ASTM C496. (2004). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. West Conshohocken, PA, DOI: 10.1520/C0496_C0496M-11.

[36] ASTM C157. (2014). Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. West Conshohocken, PA, DOI: 10.1520/C0157_C0157M-08R14E01.

[37] ASTM C1202. (2012). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. West Conshohocken, PA, DOI: 10.1520/C1202-12.

[38] Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete. Materials and Structures, 33, 574–580.

[39] Corinaldesi, V. (2011). Structural Concrete Prepared with Coarse Recycled Concrete Aggregate: From Investigation to Design. Advances in Civil Engineering, 2011(10.1155), 6.

[40] Tavakoli, M., & Soroushian, P. (1996). Drying shrinkage behaviour of recycled aggregate concrete. Concrete International, 18(11), 58-61.

[41] Huda, S., Alam, M. (2014). Mechanical behaviour of three generations of 100% repeated recycled coarse aggregate concrete. Construction and Building Materials, 65, 574-82.

[42] Xiao, J., Li, L., Tam, V., Li, H. (2013). The state of the art regarding the long-term properties of recycled aggregate concrete. Sturctural concrete, 15, 3-12.