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Durability Aspects of Concrete made with High Volume of Coarse Recycled Concrete Aggregate

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Abstract: Most applications of conventional concrete do not consider implementing the use of Recycled Concrete Aggregate (RCA) in production due to its physical properties and corresponding drawbacks. In cases where RCA is used, replacement levels of virgin aggregate with RCA typically do not exceed 15%, in order to minimize on the drawbacks. To take another approach, this paper presents results from a study aimed at maximizing the RCA replacement levels, while making only minor adjustments in mix design, to achieve both equivalent strength and durability performance of RCA concrete to their virgin aggregate counterparts. Concrete specimens were tested for compressive strength, drying shrinkage, and effects of released alkalis from RCA on triggering disruptive expansion, if used with sand that marginally meets the expansion limit. Through modifications in mix design, the drawbacks of RCA (reduced strength, increased drying shrinkage, and promoting ASR potential) were successfully mitigated at coarse RCA replacement levels up to 100%. Through the use of higher replacement levels of RCA in the production of concrete, the environmental impacts of virgin aggregate harvesting may be reduced, as well as providing a more economical means of disposing of waste concrete for ready mix producers.

1 Introduction

Among the vast quantity of concrete supplied by ready mix producers each year, aggregate yards contain heaps of virgin aggregate used in the production, but are also filled with a large amount of hardened concrete awaiting proper processing and disposal. While some of this concrete is currently re-processed into RCA, and sold as granular base material, ready mix producers are reluctant to implement RCA into their concrete mixes, and thus are not able to take full advantage of these materials. The reluctance to incorporate RCA into their mix designs stems from the drawbacks of the properties of RCA, among which reduced strength (Hansen, 1986), increased drying shrinkage (Sagoe-Crentsil, Brown, & Taylor, 2001), and the possibility of promoting of Alkali-Silica Reactivity (ASR), are major potential concerns which this study focused to address.

There are two main types of RCA, each with their own distinct features; Reclaimed RCA and Return-to-Plant RCA. Reclaimed RCA originates from the demolition of existing structures and is processed back into aggregate. This variant of RCA has typically undergone proper curing and placement procedures, required in order to satisfy the criteria specified for its original purpose, but has also been exposed to different degrading conditions over its service life, and thus may leave undesired residuals inside the mortar of the aggregate such as chlorides. This material typically also contains a certain level of particulate contaminants such are asphalt chunks, wood chips, corroded steel slivers, or others, collected from the demolition site, and brought back to the processing plant. Return-to-Plant RCA, or otherwise known as “Clean” RCA, is the end product of processing the hardened washout concrete from trucks into granular material. Though this ‘clean’ material is typically free of (or contains minimal) contaminants, it also suffers from a lack of proper placement and curing, and is unable to form a strong paste matrix due to the excessive water added into the mix to wash it out of the drum.

Depending on the type of RCA used, it is thus apparent that the deciding factor on the properties of the aggregate becomes the composition of the residual mortar. A diluted paste matrix reduces the overall density of the material (Limbachiya, Koulouris, Roberts, & Fried, 2004), and also lowers the compressive strength. The workability of RCA concrete mixes is reduced by the increased absorption rate of the RCA (Rahman, Hamdam, & Zaidi, 2009). By replacing the virgin aggregate with RCA, the overall paste volume (including both residual and new paste) is increased significantly, and thus contributes to significant increases in drying shrinkage (Tavakoli & Soroushian, 1996). Finally, the residual paste may contribute to alkali-aggregate reactivity due to its alkali and calcium hydroxide contents. These are the three main parameters evaluated in this study.

The properties (specifically compressive strength) of the new RCA concrete are highly dependent on the properties of the source concrete used to produce the RCA. Hansen (1986) has proven that RCA-concrete made at a w/cm ratio equivalent to (or higher than) the source concrete, is able to obtain compressive strength equivalent to that of the source concrete. Furthermore, Zhang and Ingham (2010) reported that all grades of source RCA were suitable to produce concrete with compressive strength up to 20 MPa. When GGBS was incorporated into the mix design with RCA, Berndt (2009) observed no significant reductions in compressive strength. This paper presents the results of an investigation into the properties and durability of moderate strength concrete containing a high volume of coarse RCA.

2 Objectives and Scope

The study aims at developing more concrete applications that can safely incorporate a large volume of RCA. One of such applications is concrete of moderate strength (15-20 MPa), which can be used in residential or highway median concrete. The experimental program evaluates the compressive strength, long-term drying shrinkage, and potential for alkali-silica reactivity when reactive sand, that marginally meets the expansion limit, is used in the same concrete mix. To further reduce the carbon footprint of the mixes, and relate to current practices of concrete production in Ontario, the use of Ground, Granulated Blast Furnace Slag (GGBS) is also incorporated and evaluated in the mixes. The use of Water Reducing Admixture (WRA), and Shrinkage Reducing Admixture (SRA) to reduce drying shrinkage, was also evaluated. By better understanding the performance of incorporating large volumes of RCA into concrete production, the ultimate goal of this project is to produce a feasible approach for production of RCA concrete that would minimize both economic and environmental impacts.

3 Materials and methods

3.1 Aggregate

Trial mixes were cast using Natural Sand (NS) as fine aggregate, in combination with either Dolostone Virgin Aggregate (VA) or RCA as coarse aggregate. RCA was sieved to conform to the gradation requirements of Group 1 according to CSA A23.1-09 for a coarse aggregate with 20 mm nominal size. All RCA is, according to the supplier, comprised of approximately 75% Return-to-Plant RCA and 25% Reclaimed RCA from previously demolished structures of unknown origin. Further aggregate properties are shown below in Table 1.

Table 1: Fine and coarse aggregate properties

	Fine Aggregate	Coarse Aggregate	
	Natural Sand	VA	RCA
Bulk Relative Density (kg/m^3)	2640	2600	2330
Dry-Rodded Density (kg/m^3)	-	1670	1420
Absorption (%)	0.95	0.9	5.55

3.2 Chemical Admixtures

In order to account for the potentially harsh climate experienced in Canada, the use of Air Entraining Admixture (AEA) is essential to improve freezing and thawing resistance of Class R concrete. All mixes thus incorporated the use of AEA. As RCA is notorious for its high drying shrinkage, the use of WRA (to reduce water and cementing materials content), and SRA to reduce shrinkage, were evaluated.

3.3 Trial Mixes and Specimens

A total of 23 trial mixes were tested in this study. Each mix was tested for compressive strength using cylinders (100 mm diameter, 200 mm length) at 7 and 28 days. In addition, drying shrinkage and expansion due to ASR were tested using 75x75x285mm prisms Trial mixes were used to investigate the effect of different parameters on drying shrinkage including the use of GGBS, replacement level of RCA, and the use of WRA, and SRA. Results displayed are based on an average of three test specimens. The within-test variation was monitored for all samples.

Table 2: Trial mixture proportions

Mix Label	Portland Cement (kg/m^3)	GGBFS (kg/m^3)	VA (kg/m^3)	RCA (kg/m^3)	Natural Sand (kg/m^3)	Water (kg/m^3)	w/cm ratio	Air Content (%)
V-1	250	-	1035	-	785	155	0.62	6.5
V-2	250	-	1035	-	732	175	0.7	5.6
V-FT	250	-	1035	-	732	175	0.7	5.5
V-S30-1	175	75	1035	-	781	155	0.62	6.0
V-S30-2	175	75	1035	-	727	175	0.7	5.8
V-S30-SR	175	75	1035	-	780	155	0.62	7.5
V-S30-WR	157.5	67.5	1035	-	843	157.5	0.7	8.0
V-S50	125	125	1035	-	778	155	0.7	4.5
R-1	250	-	-	880	839	155	0.62	9.5
R-2	250	-	-	880	839	155	0.62	6.8
R-4	250	-	-	880	839	155	0.62	6.6
R-FT	250	-	-	880	839	155	0.62	5.0
R-SR	250	-	-	880	839	155	0.62	6.4
R-SR-3Max	250	-	-	880	839	155	0.62	6.6
R-S30	175	75	-	880	834	155	0.62	6.5
R-S30-FT	175	75	-	880	834	155	0.62	6.6
R-S30-SR	175	75	-	880	834	155	0.62	8.0
R-S30-SR-2Min	175	75	-	880	834	155	0.62	7.0
R-S30-SR-3Max	175	75	-	880	834	155	0.62	5.0
R-S30-WR	157.5	67.5	-	880	897	139.5	0.62	7.0
R70-V30	250	-	311	616	818	155	0.62	7.2
R70-V30-S30	175	75	311	616	818	155	0.62	6.0
R70-V30-S30-2	175	75	311	616	818	155	0.62	6.6

Table 3: Mix identification legend

Variable	Definition
V	100% Virgin Aggregate
R	100% Coarse RCA
S30 or S50	30% or 50% GGBS (By Mass of Cementing Materials)
R70-V30	70% Coarse RCA & 30% Virgin Aggregate (By Volume)
WR	Addition of Water Reducing Admixture
SR Min & Max	Addition of Shrinkage Reducing Admixture at 5L/m^3 2.5L/m^3 & 7.5L/m^3 of SRA Addition

Houphouet-Boigny and Kouadio (2011) reported low decreases in compressive strength (relative to VA concrete) when a cementing materials content < 300kg/m^3 is used. All mixes in the study contained a relatively low cementing materials content of 250 kg/m^3. Table 2 summarizes the proportions of all trial mixes. It is to be noted that all mixes produced with VA, and RCA, were tested at a w/cm ratio of 0.7 and 0.62, respectively, unless otherwise specified. For clarity of coding, Table 3 displays the coding legend for all mixes.

3.4 Test Procedure

Compressive strength testing was performed using concrete cylinders having an approximate diameter of 100 mm and a length of 200 mm. Results were taken after 7 and 28 days of curing in accordance with ASTM C 39.

Drying shrinkage testing was performed in accordance with ASTM C 157 using concrete prism samples having approximate dimensions of 75 x 75 x 285 mm. Samples were cured in lime-saturated water prior to being placed into drying conditions at an age of 7 days. It is to be noted that all drying shrinkage results are in reference to the 7-day initial reading.

The reactivity of the coarse RCA used in this study was evaluated using concrete prisms, in accordance with CSA A23.2-14A, for a period of 90 weeks. Utilizing Marginally Reactive Sand (MRS), in combination with coarse RCA, testing was done in order to determine whether the combinations would trigger further ASR expansion.

4 Discussion of Test Results

4.1 Compressive Strength

As an example of applications that involve the use of the concrete mixtures, investigated here is Class R concrete as per CSA A23.1-09, which specifies a minimum 28-day compressive strength of 15 MPa for air-entrained, residential wall concrete, with a maximum allowable w/cm ratio of 0.7. All VA control mixes (Figure 1), produced at the maximum w/cm ratio, marginally passed this requirement. Mixes V-1 and V-S30-1 displayed a slightly higher compressive strength, due to a reduced w/cm ratio of 0.62. By maintaining a maximum w/cm ratio of 0.62, all RCA mixes were also able to surpass this minimum requirement, as seen in Figure 2. It is to be noted that mix R-1 was unable to meet this minimum requirement, as the mix resulted in excessive entrained air content (9.5%). This was due to the early addition of the AEA into the mixing water. This finding emphasized the importance of sequencing for the batching process.

To evaluate workability retention, all mixes were held for a period of 45 minutes, following the batching process, simulating travel time of the truck. During this time, water was added to maintain the high slump requirements for this class of concrete, and as such, replicating the likely scenario of water addition post-batching to the mix once the truck leaves the plant. It has been widely documented that such practice may significantly reduce the performance of concrete, and thus required addressing.

It is to be noted that all subsequently added water was originally withheld from the original mix design. This was to ensure that a final w/cm of 0.62 is ultimately maintained once the water had been re-introduced, and still satisfy the maximum w/cm criteria for Class R concrete. Even with such tampering, all mixes were able to meet the minimum compressive strength requirement of Class R residential wall mixes. Most mixes even surpassed the minimum 20 MPa requirement for residential floor applications, which do not require air-entrainment.

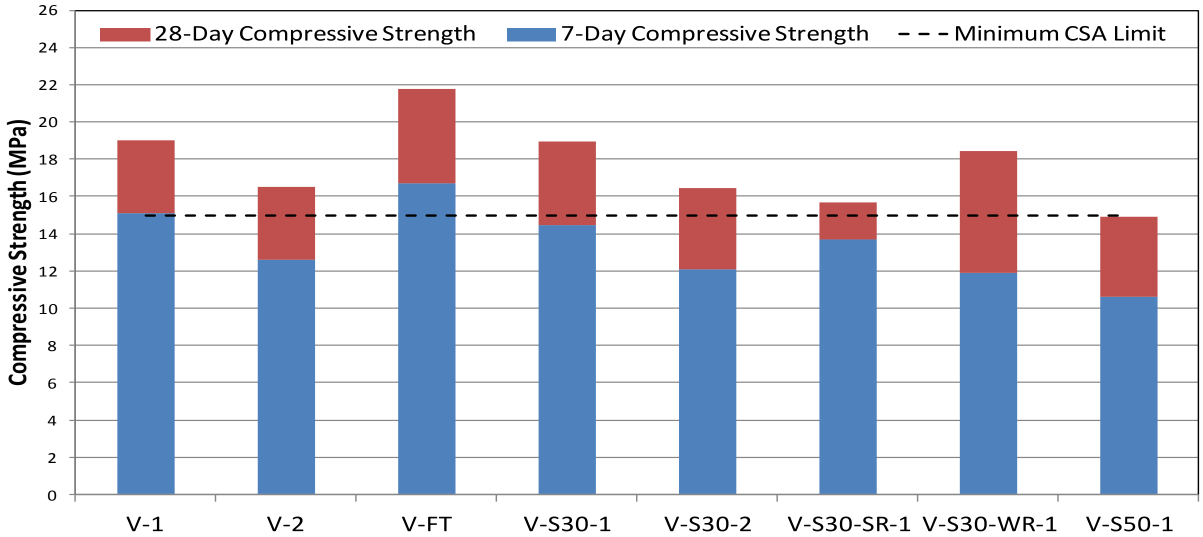

Figure 1: Compressive strength (VA)

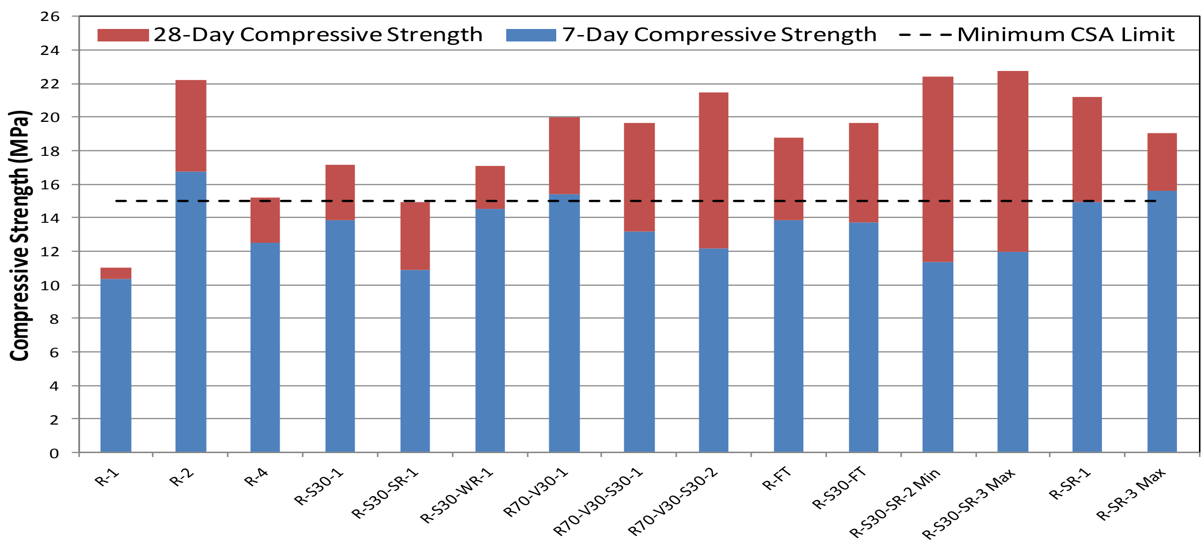

Figure 2: Compressive strength (RCA)

4.2 Drying Shrinkage

Though CSA A23.1-09 does not specify a requirement on drying shrinkage of Class R concrete, it is an important factor to be tested at high-volume RCA replacement levels, due to the overall increased mortar content of the concrete produced. Both the residual mortar from the RCA, as well as the high w/cm ratio paste (forming the new mortar), contribute highly toward what makes RCA concrete notorious for drying shrinkage problems.

Figure 3 displays the drying shrinkage curves obtained for various trial mixes containing VA and RCA up to the age of 180 days. As shown in Figures 3 (a) and (b), various control mixes were cast at a w/cm ratio of 0.7, using only VA, to establish a baseline for shrinkage of conventional Class R concrete. An average 180-day shrinkage, ranging between 0.05 – 0.06%, was observed to be common in VA mixes conforming to Class R requirements. Seen in Figure 3 (a), the replacement of 30% PC with GGBS exhibited negligible differences in drying shrinkage, as was also reported by Hooton et al. (2004).

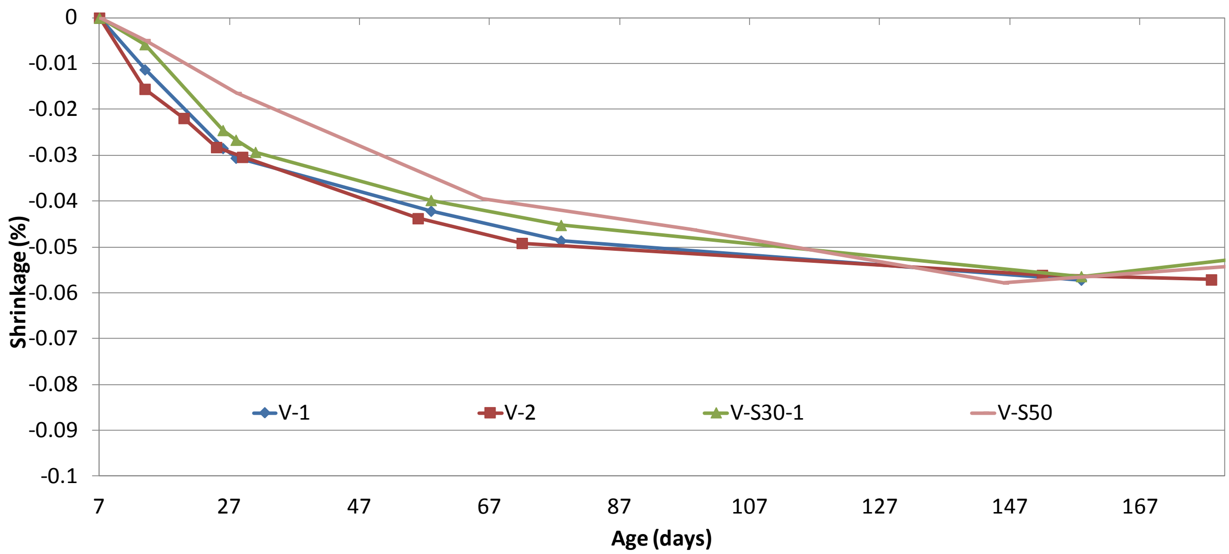

Figure 3: (a) Drying shrinkage of mixtures with virgin aggregates and GGBS replacement

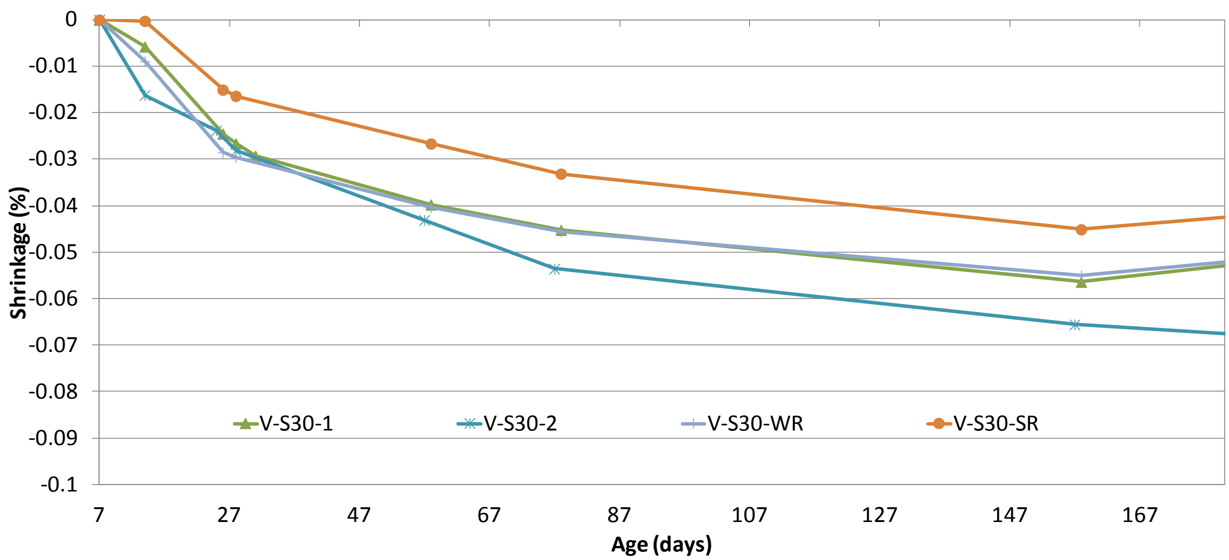

Figure 3: (b) Drying shrinkage of mixtures with virgin aggregates, WRA, and SRA

Figure 3 (b) shows the effects of adding chemical admixtures to concrete conforming to Class R requirements using VA. With respect to drying shrinkage, the use of water-reducing admixture (to reduce the overall cementing materials content by 10%) did not display any improvement. In a similar study, Sagoe-Crentsil et al. (2001) investigated the effects of varying cementing content by 5% and discovered similar results. As also reported by Tavakoli and Soroushian (1996), it is clear from the results in Figure 3 (b) that the w/cm is the main factor affecting shrinkage. The role of total cementing materials is very minimal for the mixtures investigated here. Indeed, the mixes V-S30-1 and V-S30-2 are of the same composition except for the w/cm ratio. The shrinkage of the mixture with w/cm of 0.70 was higher than that of w/cm of 0.62, However, the use of SRA in these mixes was able to reduce the overall shrinkage by approximately up to 20% overall.

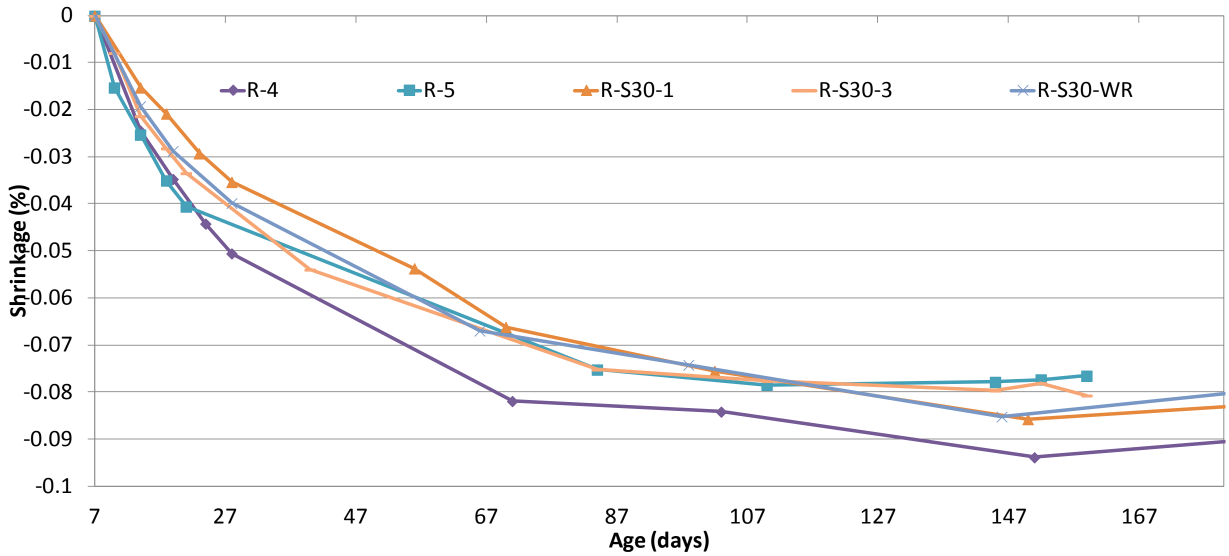

Figure 3: (c) Drying shrinkage of mixtures with 100% RCA replacement and 30% GGBS

Figure 3 (c) displays various mixes cast at a w/cm ratio of 0.62 with a complete replacement of coarse aggregate by RCA. A common overall shrinkage of approximately 0.08% was observed for mixes containing only RCA as coarse aggregate. This translates into an approximate 50% increase in drying shrinkage compared to mixtures containing only VA. As was the case with VA, the addition of GGBS (at 30% replacement) did not play a significant role in reducing the effects of drying shrinkage.

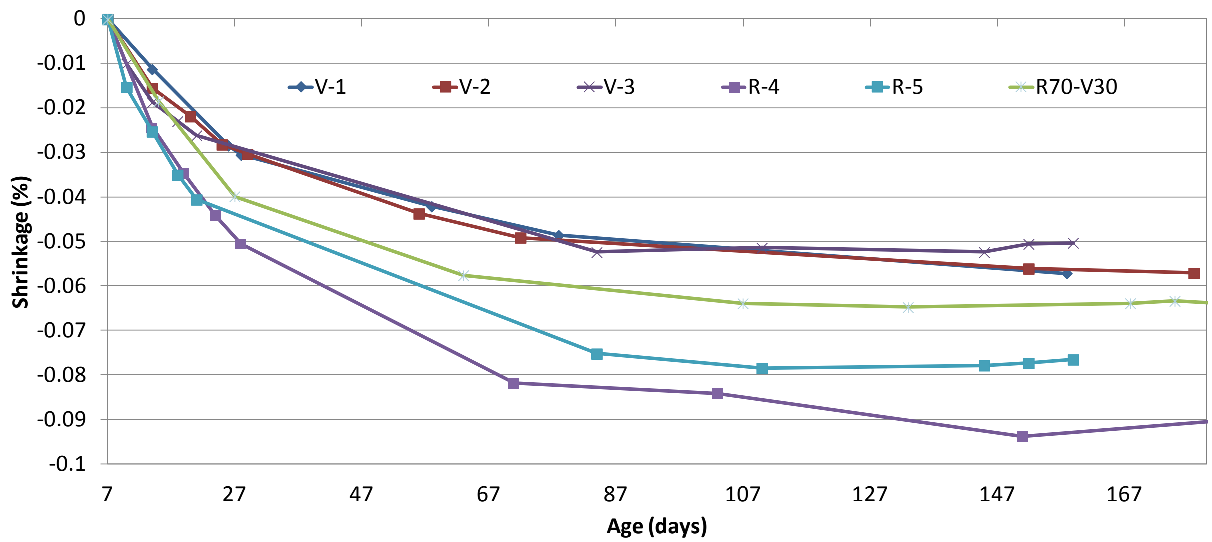

Figure 3: (d) Drying shrinkage of mixtures containing varying RCA replacement levels

Figure 3 (d) displays mixes cast at a w/cm ratio of 0.62 but with a blend of RCA and VA at a ratio of 30:70% of the total coarse aggregate content. These mixes exhibited an average overall drying shrinkage of 0.065%; only an 8-20% increase relative to that of 100% VA. Relative to the high replacement level of RCA, this increase in drying shrinkage may be easily mitigated in most applications.

Figure 3 (e) displays mixes cast using both 30% GGBS replacement and a 70% replacement of RCA at 0.62 w/cm ratio. It can be observed that drying shrinkage reduces (relative to VA mixes) from an increase of 50% to only 20% when the RCA replacement level is reduced from 100% to 70%, respectively.

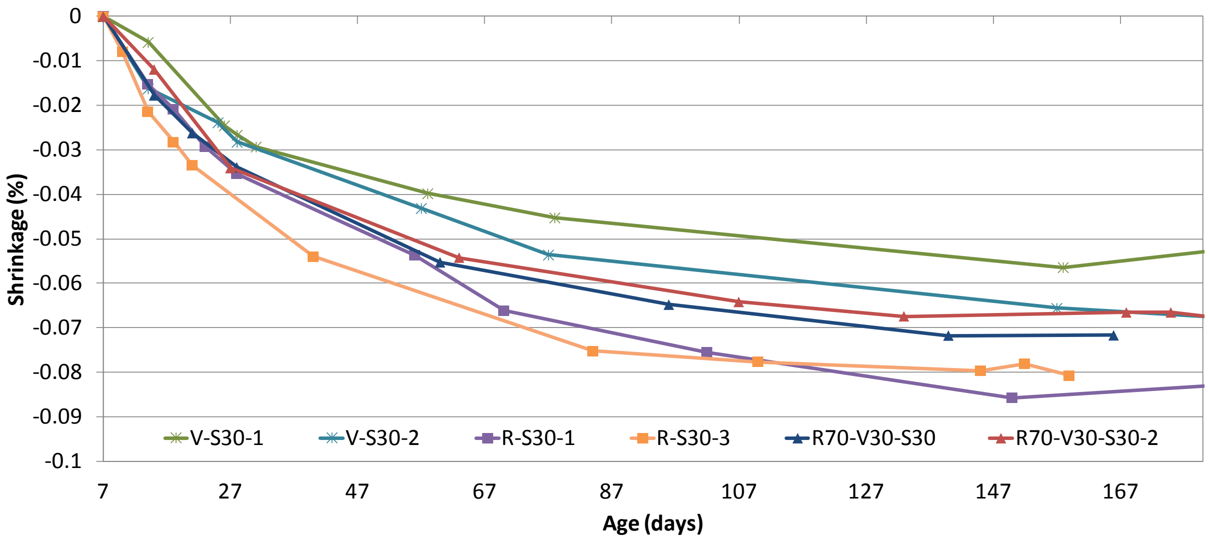

Figure 3: (e) Drying shrinkage of mixtures containing both 70% RCA replacement and 30% GGBS

Figure 3 (f) displays mixes cast using various dosages of SRA to control drying shrinkage. Mixes were cast by varying from the manufacturer's minimum (R-S30-2Min) to maximum (R-S30-3Max) recommended dosage of SRA. Though the trend over time remains similar to that of mixes without SRA, the overall shrinkage remains significantly lower. Of particular significance is the fact that, at the maximum recommended dosage, the SRA was able to completely cancel out the increased drying shrinkage effects of RCA, and reduce it down to that of VA, even at 100% replacement.

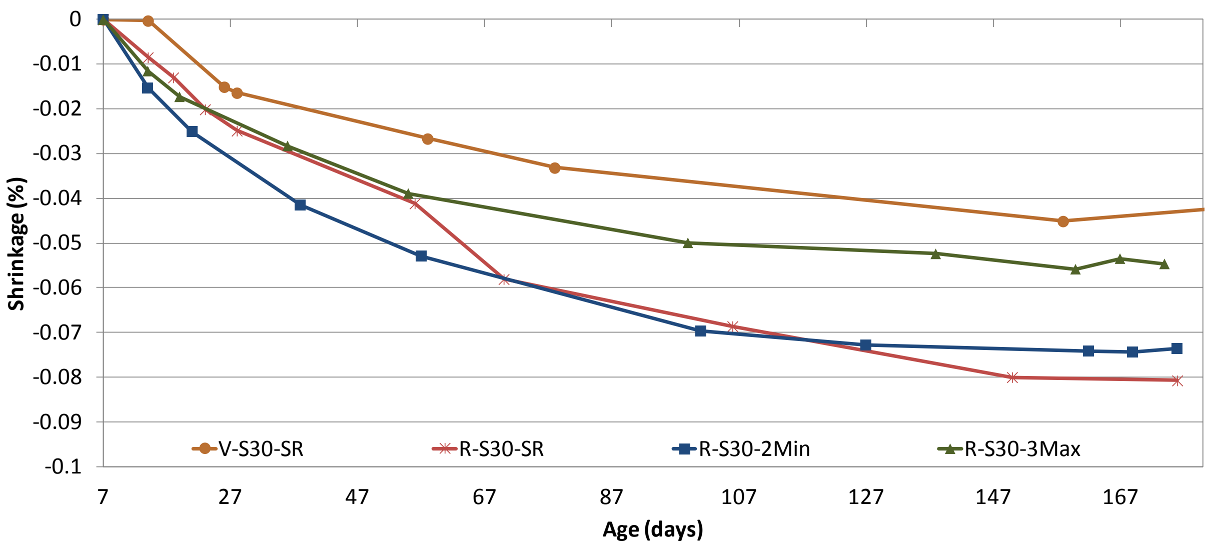

Figure 3: (f) Drying shrinkage of mixtures with varying SRA dosages

4.3 Alkali-Silica Reactivity (ASR)

The sand used in this study (MRS) marginally met the expansion limit when tested according to CSA A23.2-14A. Figure 4 displays the expansion of MRS with both Non-Reactive Coarse (NRC) aggregate and RCA. Utilising such sand allowed for direct testing of the effects of the alkalis released from the residual mortar of the RCA on triggering excessive expansion in the marginally reactive sand. By replacing the NRC with RCA, no further expansion was observed, and thus demonstrating that RCA does not have a tendency to trigger further expansion in concrete with MRS.

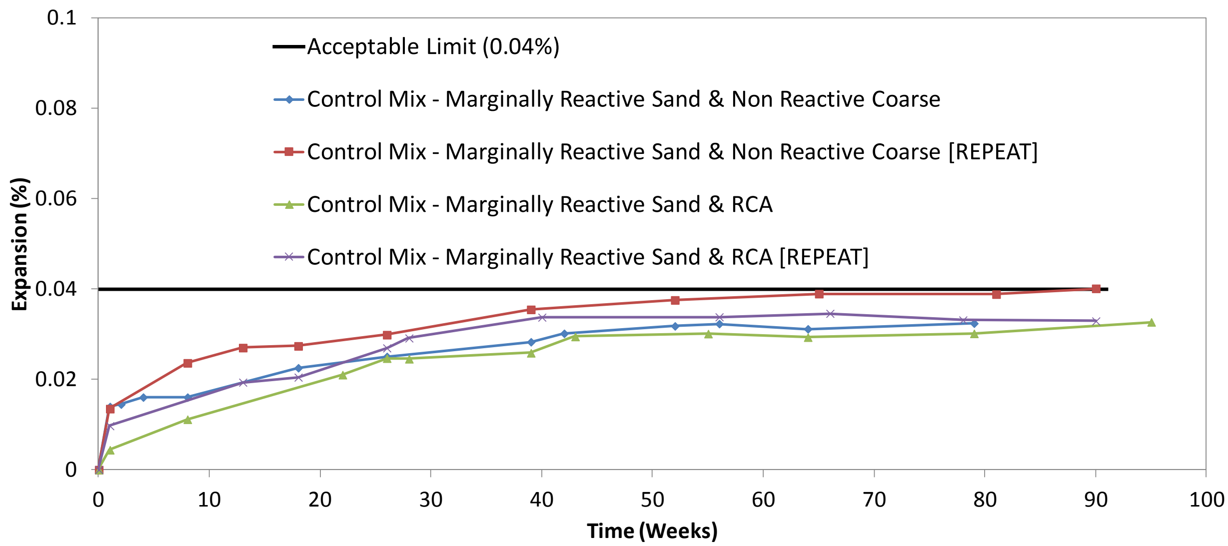

Figure 4: Reactivity of marginally reactive sand and RCA

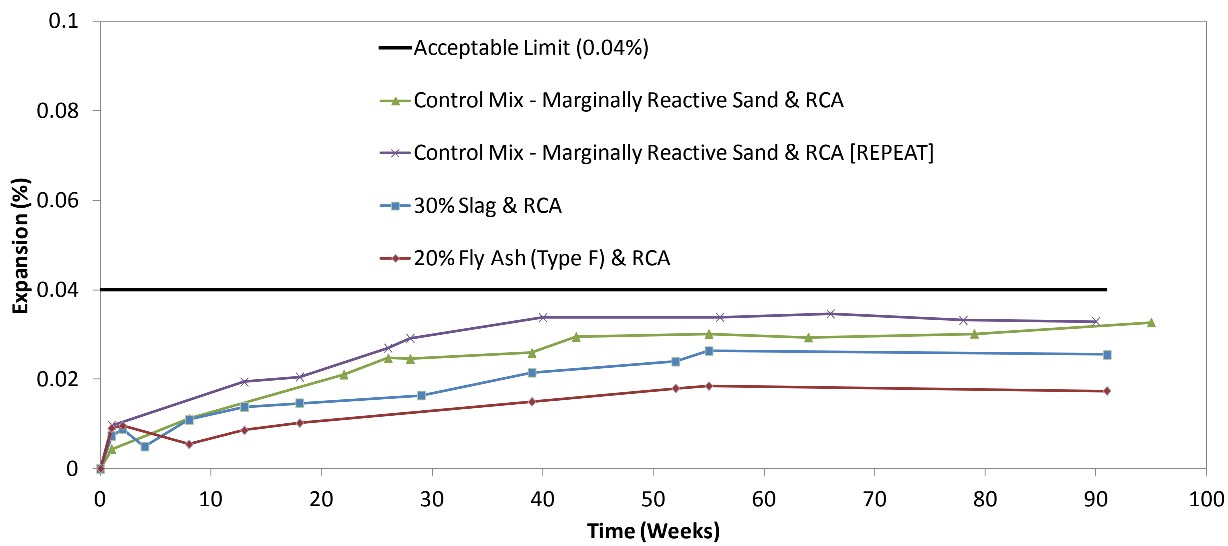

Figure 5: Reactivity of marginally reactive sand and RCA with SCMs

Figure 5 displays the effects of incorporating SCMs into the mix to mitigate ASR. It was observed that a 30% replacement of PC with GGBS, or a 20% replacement of Type F Fly Ash, in combination with RCA, was able to reduce the effects of ASR far below the acceptance even when the marginally reactive sand was used in the mix.

5 Conclusions and Future Work

Through slight modifications in mix design, such as the reduction in maximum w/cm ratio, the minimum requirements (compressive strength and air) of Class R concrete were easily satisfied, even when RCA replacement level of 100% was used. As is standard practice in Ontario, incorporating a 30% substitution of GGBS was able to improve environmental and economical feasibility of all mixes, while still maintaining the required compressive strength, and not impacting the overall drying shrinkage of the mixtures.

Relative to conventional (Class R) concrete, using VA, the trial mixtures displayed an increase of up to 50% in overall drying shrinkage when a substitution level of 100% coarse RCA was implemented. It may be assumed that a non-linear relationship exists between the replacement level of RCA in RCA-concrete and its drying shrinkage. This was observed when reducing the replacement level from 100% to 70% caused the increase in drying shrinkage (relative to VA) to decrease from 50% to approximately 20%. By investigating other various replacement levels of RCA, an optimal balance may be achieved to minimize on drying shrinkage and maximizing the volume of RCA.

An increase in compressive strength, and reduction in drying shrinkage, was observed for the use of WRA and SRA, respectively. WRA, when used to reduce cementing material content in the mix, did not have any impact on overall drying shrinkage, which is believed to be related to the fact that both mixtures had the same w/cm. SRA proved to be a substantial contributor to mitigating the effects of drying shrinkage of high volume RCA concrete, when used at the correct dosage. In fact, when sufficient SRA was added, the effects of drying shrinkage were completely eliminated, even at 100% replacement.

In terms of alkali-silica reactivity, a replacement level of 100% coarse RCA did not display any tendency to promote further reaction when used with marginally reactive sand. This suggested that the reaction was perhaps limited to the amount of level of reactivity in the sand, and not to the amount of alkalis in the system. This is assuming that RCA releases alkalis to the mix (Shehata & Thomas, 2010).

Though many challenges are faced when using RCA in new concrete, it remains an alternative to conventional production that is well worth investigating. Overall, the study can conclude that viable options are available, in terms of mitigating the effects of RCA's drawbacks in concrete performance. RCA was able to meet the requirements of moderate strength concrete at replacement levels up to 100% and remains to be tested in higher performance applications.

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