Cement and Concrete Research 40 (2010) 575–582

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali–silica reaction

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ARTICLE INFO

Article history:
Received 5 November 2008
Accepted 13 August 2009

Keywords:
Alkali–Aggregate Reaction (C)
Reclaimed concrete aggregate
Fly Ash (D)
Lithium Compound (D)
SEM (B)

ABSTRACT

This paper presents results from a research program that focused on studying the reactivity of reclaimed concrete aggregate (RCA) produced from concrete affected by alkali–silica reaction (ASR). The results showed that RCA produced from ASR-affected concrete causes significant expansion when used in new concrete. The expansion was similar to that produced in concrete containing the reactive aggregate used originally in the old concrete. It is believed that crushing the old concrete exposed fresh faces of the reactive aggregate which causes renewed reaction and expansion in the new concrete. The alkalis contributed from the RCA are also believed to contribute to the expansion. The amount of supplementary cementing materials required to mitigate the expansion in new concrete containing ASR-affected RCA was higher than those normally needed in concrete containing the virgin reactive aggregate. The results showed a good agreement between the 14-day expansion of accelerated mortar bars and the expansion of concrete prisms.

1. Introduction

Environmental issues resulting from construction waste are a major concern. Each year 200 million tons of construction waste is continuously discarded in landfills [1]. Most of the disposed construction materials can be recycled, thus reducing the accumulation of waste disposed in landfills. Concrete is of great concern when considering wasted materials as it constitutes the largest portion of the total debris after demolition. For example, when an apartment building is demolished concrete amounts to approximately 30 to 40 wt.% of the wreckage [2].

With time, structures may deteriorate to a point where repair is not cost effective, or become obsolete and need to be replaced. The debris that remains after demolition needs to be appropriately re-used and not disposed in landfills. It makes sense to seek possible uses of these materials such as being recycled into new structures. In Ontario, current Provincial specifications permit the recycling of RCA as granular base in pavements but not into new concrete construction. Recycling demolished concrete as aggregate in new concrete is also an option that not only reduces the amount of construction wastes disposed in landfills but also reduces the consumption of non-renewable resources, such as natural aggregate. However, the use of reclaimed concrete aggregate (RCA) in new structures requires thorough research to make sure that the durability of the new concrete is not compromised, especially if the old concrete was suffering from alkali–silica reaction.

Many highway and hydraulic structures in North America have been reported to be affected by alkali–silica reaction (ASR). In Ontario alone, as early as the beginning of the 1980s, it was reported that more than 130 highway structures were affected by alkali–aggregate reaction [3]. It is anticipated that most of these structures will be demolished as they approach the end of their service life. Recycling of the reclaimed concrete in new structures may be a viable option from environmental and economic standpoints, especially if the structures are in locations that are far from natural aggregate sources. So, it is imperative to investigate the potential reactivity of the reclaimed concrete aggregate and develop preventive measures, if needed.

The use of supplementary cementing materials (SCMs) as preventive measures against ASR has been adopted in many new structures. Much research has shown that the use of the right amount and type of SCM reduces the reaction and expansion due to ASR to a very low level [4–7]. The efficacy of these materials in mitigating ASR is attributed, mainly, to their ability to reduce the alkalinity of pore solution [8]. Field observations of structures have confirmed the efficacy of SCM in providing good performance [9].

Lithium salts have been reported by various researchers to be effective, when used in appropriate dosages, in counteracting ASR [10–14]. Lithium nitrate has been found to be the most effective salt as it does not raise the alkalinity of the pore solution as is the case with lithium hydroxide [11]. The appropriate dosage of lithium has been found to

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doi:10.1016/j.cemconres.2009.08.008

have no correlation with the aggregate expansivity or the petrographic nature of the aggregate [12]. Research has also shown that considerable amounts of lithium are bound by the hydration products of the cementing materials [13]. The mechanism by which lithium mitigates ASR is not fully known. One of the mechanisms put forward by Kurtis et al. [14] suggests that lithium reduces the repolymerization of ASR gel, and hence reduces its ability to expand. However, the study of Kurtis et al. was performed using lithium chloride.

Torben Hansen [15] in a review of recycled aggregate issues, noted that more research was needed to clarify the issues and difficulties associated with recycling alkali–aggregate reactive concrete into new concrete. He also recognized the lack of an accepted test method for evaluating this problem. Only a very limited amount of research has been spent on reactivity of RCA. A study, in the United States, on RCA from a section of Interstate I-95 near Gardener, Maine, showed that ASR-affected RCA caused high expansion in the new concrete. The expansion was higher than that produced in concrete containing the aggregates originally used in the concrete which was a fine-grained quartzite coarse aggregate [16]. There is also an example from Wyoming (Bob Rothwell, Wyoming DOT, personal information) where the use of fly ash did not prevent the re-occurrence of damage in a concrete pavement on I-80 made with alkali–aggregate reactive RCA from the earlier pavement.

The main objectives of the research presented in this paper were: (1) to investigate the reactivity of RCA produced from ASR-affected concrete containing highly reactive Canadian aggregate, (2) to find out if current ASR tests including the accelerated mortar bar test are able to evaluate the reactivity of RCA and the efficacy of common preventive measures such as SCM, and (3) to determine the type and levels of preventive measures that are needed to mitigate the expansion in new concrete containing ASR-affected RCA.

2. Materials and experimental details

2.1. Materials

The RCA used in this study was obtained from the Ontario Ministry of Transportation outdoor exposure site in Kingston, Ontario, Canada. The material was a concrete block (0.6×0.6×2 m) placed in 1991 using CSA Type 10 cement (a normal Portland cement) and a highly expansive alkali-reactive siliceous limestone coarse aggregate from the Spratt quarry in Ottawa, Ontario. The rock contained about 9% silica. Because of the very fine crystalline nature of the silica it was not observable under the microscope using normal techniques. The non-reactive fine aggregate was natural sand composed of igneous and high-grade metamorphic rocks and derived minerals. The construction of the concrete outdoor exposure site is described in a paper by Afrani and Rogers [17]. The expansion of the concrete after eight years is described in a paper by Rogers et al. [18] and the expansion of the concrete after 14 years and petrographic characteristics of the damaged concrete are described in a paper by Hooton et al. [19].

After 12 years of exposure, the block (a spare) was removed and crushed into aggregate. At that time, the concrete block had experienced severe expansion (linear expansion of 0.19%) and associated cracking. The concrete block was broken into boulder-size pieces using a backhoe ram and a laboratory jaw crusher was used to produce coarse and fine RCA.

The Dry Bulk Relative Density and absorption of the coarse RCA were 2333 kg/m^3 and 5.1% respectively. Samples of Spratt aggregate (the virgin aggregates originally used in the RCA) were also collected from a stockpile at the Ontario Ministry of Transportation. The Dry Bulk Relative Density and absorption of Spratt virgin aggregate are 2664 kg/m^3 and 0.6%, respectively. Two GU Portland cements (PCs) of low and high-alkali contents and six different SCMs were used in the study. The chemical analysis of the PCs and SCMs is listed in Table 1. Lithium nitrate ($LiNO_3$) was also used as a preventive measure.

Table 1
Major oxide composition of the Portland cements and SCMs determined by XRF (wt.%).

Sample	LAPC[a]	HAPC[b]	SF[c]	SG[d]	F-LA[e]	F-HA[f]	CI-LA[g]	CH-LA[h]
CaO	62.4	62.8	0.27	43.2	4.43	6.42	17.0	28.7
SiO_2	20.1	19.6	96.2	34.4	55.7	61.3	40.2	33.3
Al_2O_3	4.43	5.35	0.35	7.4	27.4	16.8	21.4	18.2
Total-Fe_2O_3	2.80	2.29	0.10	0.94	5.59	4.62	9.92	6.45
MgO	3.01	2.43	0.91	9.30	1.56	2.15	4.23	5.32
SO_3	3.60	4.10	0.25	0.83	0.26	1.12	2.46	2.59
K_2O	0.44	1.13	0.51	0.58	2.29	0.98	1.04	0.33
Na_2O	0.27	0.21	0.21	0.57	0.44	3.68	1.36	1.94
TiO_2	0.23	0.31	0.13	0.44	0.67	0.95	1.39	1.45
P_2O_5	0.13	0.11	0.13	0.00	0.31	0.54	1.10	0.88
Total-C	n.a.	n.a.	1.35	0.21	1.58	n.a.	1.29	n.a.
Na_2O_e	0.56	0.96	0.55	0.95	1.95	4.30	2.10	2.16
Fineness[i]	n.a.	n.a.	n.a.	n.a.	26.7	n.a.	14.9	n.a.

Notes: Portland cements, slag and silica fume are from Ontario, Canada; fly ashes are from south-east US.
[a] LAPC: Low-Alkali GU Portland Cement.
[b] HAPC: High-Alkali GU Portland Cement.
[c] SF: Silica Fume.
[d] SG: Slag.
[e] F-LA: Fly Ash Type F (CaO < 8 wt.%) with low-alkali content.
[f] F-HA: Fly Ash Type F (CaO < 8 wt.%) with high-alkali content.
[g] Fly Ash Type CI (8 wt.% < CaO < 20 wt.%) with low-alkali content.
[h] Fly Ash Type CH (CaO > 20 wt.%) with low-alkali content.
[i] Fineness (%retained on 45-μm sieve).

2.2. Experimental procedures

2.2.1. Concrete prism test

The concrete prism test (CPT) according to CSA A23.2-14A [20] was used to evaluate the reactivity of the RCA and the efficacy of preventive measures. Using the 60:40 coarse-to-fine aggregate ratio by mass resulted in a coarse mix, which was expected since the RCA has a relatively low relative density. A volume of dry-rodded coarse aggregate of 0.69 vol.% of unit volume of concrete was found to produce workable and homogeneous mixtures. This ratio, which lies within the limit of CSA A23.2-14A [20], was then used in all the tested samples. The dry-rodded density of coarse aggregate is the bulk density of an aggregate sample compacted in a standardized manner as per ASTM C 29 [21]. In this method, the aggregate is placed in three layers in a container of known volume (7.6 L in this study), and each layer is rodded with 25 strokes of a standard tamping rod. The dry-rodded density is the determined mass of the aggregate per unit volume of the container. The determined value for the RCA used in this study was 1385 kg/m^3. Hence, 1 m^3 of concrete contains 0.69 m^3 of dry-rodded RCA or 0.69 × 1385 = 956 kg. The RCA was not washed to prevent any leaching of alkalis from its residual mortar. This is to make sure that the effect of alkalis contributed from RCA is considered in the investigation. However, two concrete mixtures (one with no SCM and the other with 25 wt.% of the fly ash F-LA) were tested with washed RCA to investigate whether or not washing the RCA can have a role in reducing the expansion. Washing the RCA was done by soaking the aggregate in a water-filled pail, placing a water hose inside the pail, and allowing the water current to overflow from the top of the pail. This washing operation continued for 18 h.

To examine the effects of alkali loading on expansion, additional control samples (with no SCM or lithium nitrate) were prepared at alkali levels of 0.56 wt.%, 0.80 wt.% and 1.5 wt.% Na_2O_e per mass of Portland cement. The 0.80 wt.% Na_2O_e was achieved by mixing the two GU cements of 0.96 wt.% and 0.56 wt.% Na_2O_e at the required ratio.

The SCMs listed in Table 1 were used at different replacement levels in binary and ternary blends with the high-alkali GU Portland cement (HAPC). The alkali content was boosted to 1.25 wt.% per mass of PC using reagent grade NaOH. Lithium nitrate was also investigated at different dosages. Some samples were tested by adding the lithium to the mixing water while others were tested by pre-soaking the air-dry RCA in the lithium and half of the mixing water for 24 h prior to mixing. Some mixtures contained both lithium nitrate and 20 wt.% F-LA fly ash. For all mixtures containing lithium, the HAPC (0.96 wt.% Na_2O_e) was used without boosting the alkalis to 1.25 wt.% Na_2O_e. Tables 2 and 3 list the mixture proportions of the samples investigated in this study.

2.2.2. Accelerated mortar bar test

The accelerated mortar bar test (AMBT) was conducted following ASTM C 1260 [22] and ASTM C 1567 [23] with the objective of investigating whether or not this test method, AMBT, is able to evaluate the reactivity of RCA and the efficacy of SCMs as preventive measures. The results from the concrete prism test were used as a benchmark to evaluate the suitability of the AMBT in testing RCA. Mortar samples without SCM were tested following ASTM C 1260 [22] and those with SCM following ASTM C 1567 [23]. Cementing blends investigated using the AMBT were those used in concrete prism test, except for two blends: 5/25 SF/CH-LA and 5/25 SF/Slag. A control sample (with no SCM) was tested using the HAPC with no change in the alkali loading. The aggregate samples were prepared by crushing and sieving the coarse RCA to the required gradation. The fine fraction produced by the primary crushing (first crushing by jaw crusher) was found to produce considerably lower expansion than the sample prepared by re-crushing the coarse RCA (secondary crushing), as will be shown in Fig. 7. Based on that, all accelerated mortar bar tests were performed using aggregate produced by re-crushing and sieving the coarse RCA.

2.2.3. Concrete microbar test

The RILEM concrete microbar test (CMBT) [24] was used along with the accelerated mortar bar test to evaluate the reactivity of aggregates. The test has been proposed as a promising universal test for evaluating alkali–aggregate reactivity [25,26]. In this test, concrete bars of 40×40×285 mm are cast using aggregate sizes of 4.0 to 8.0 mm at cement/aggregate ratio of 1 and w/c ratio of 0.33. No sand is used in this test method. The RILEM test is conducted on aggregate size from 4 to 8 mm with a note allowing the use of 5.0 mm to 10.0 mm aggregates. In this paper, two different RCA sizes were investigated: 4.75 mm to 9.5 mm and 9.5 mm to 13 mm. In addition, a 4.75 mm to 9.5 mm sample of the virgin Spratt aggregate was also tested using this test method. The microbars were prepared using the HAPC but without boosting the alkali content to 1.5 wt.% Na_2O_e as required by the RILEM test. After casting, the specimens were stored for 24 h at RH of 100%, then de-molded and stored in water at 80 °C for another 24 h. The initial length of the bars was then measured and the samples were stored in pre-heated 1 N NaOH solution at 80 °C, and the expansion was monitored up to 56 days.

2.2.4. Scanning electron microscopy (SEM)

Polished sections of RCA were prepared and sputtered with carbon in an Edwards Vacuum Coating System Model # 306A using ultra pure Carbon, Grade UF4S. The samples were polished using a diamond grade of 0.3 μm for final polishing. Oil was used as a cooling agent, to avoid leaching of alkalis. Polished sections were studied in a JEOL JSM6380 LV scanning electron microscope operated at 10^{-4} Torr and 20 kV in backscatter mode (BSE).

3. Results

3.1. Evaluating the reactivity of RCA

Fig. 1 shows the expansion of control concrete prisms (with no SCM) containing either coarse or fine RCA as well as prisms containing the virgin aggregate originally used in the RCA (Spratt). Two identical control concrete prism samples were tested to investigate the range of concrete expansion values that can be produced using RCA from the same source. Two expansion curves for Spratt are also presented in Fig. 1: a curve from a study by Shehata and Thomas [6] and another one from a sample tested as part of the RCA research presented in this paper. The expansion limit of 0.04% ℓ/ℓ at 1 year suggested by CSA 23.2.27A [27] is also shown on the graph. It is clear from the expansion curves that the RCA produces expansion similar to that of the Spratt. In addition, 18 h of washing the RCA with running water did not result

Table 2
Mix proportions per 1 m^3 of the RCA-concrete samples tested using the concrete prism test.

Control samples (no SCM)							
Sample ID	PC (kg)	SCM Type	SCM Mass (kg)	RCA[a]	Fine agg (kg)	Effective w/cm [b]	$LiNO_3$ (L)[c]
1.25 Na_2O_e	420	–	–	956	690	0.450	–
1.25 Na_2O_e (washed RAC)	420	–	–	956	690	0.450	–
0.56 Na_2O_e	420	–	–	956	690	0.435	–
0.80 Na_2O_e	420	–	–	956	690	0.450	–
1.50 Na_2O_e	420	–	–	956	690	0.440	–
Binary blends containing silica fume, fly ash or slag							
5% SF	399	SF	21	956	685	0.450	–
8% SF	386	SF	34	956	681	0.450	–
10% SF	378	SF	42	956	679	0.450	–
20% F-LA	336	FA: F-LA	84	956	667	0.436	–
25% F-LA	315	FA: F-LA	105	956	662	0.450	–
25% F-LA (washed RCA)	315	FA: F-LA	105	956	662	0.420	–
30% F-LA	294	FA: F-LA	126	956	656	0.450	–
20% CI-LA	336	FA: CI-LA	84	956	673	0.442	–
30% CI-LA	294	FA: CI-LA	126	956	664	0.436	–
25% CH-LA	315	FA: CH-LA	105	956	674	0.420	–
30% CH-LA	294	FA: CH-LA	126	956	670	0.420	–
50% CH-LA	210	FA: CH-LA	210	956	657	0.420	–
25% SG	315	Slag	105	956	684	0.430	–
30% SG	294	Slag	126	956	683	0.450	–
50% SG	210	Slag	210	956	678	0.420	–

[a] The RCA is composed of three equal parts of material between the 20 mm to 14 mm, 14 mm to 10 mm, and 10 mm to 5 mm sieves.
[b] Values of effective w/cm exclude correction due to absorption of aggregates and water from $LiNO_3$, if used.
[c] $LiNO_3$ used as solution of specific gravity = 1.20 and solid content of 30%.

Table 3
Mix proportions per 1 m^3 of the RCA-concrete samples tested using the concrete prism test.

Sample ID	PC (kg)	SCM		RCA[a]	Fine agg (kg)	Effective w/cm[b]	$LiNO_3$ (L)[c]
		Type	Mass (kg)				
Ternary blends of silica fume and fly ash or slag							
5/15 SF/F-LA	336	SF/F-LA	21/63	956	668	0.450	–
5/20 SF/F-LA	315	SF/F-LA	21/84	956	662	0.450	–
5/30 SF/F-LA	273	SF/F-LA	21/126	956	650	0.450	–
5/20 SF/CI-LA	315	SF/CI-LA	21/84	956	667	0.450	–
5/25 SF/CI-LA	294	SF/CI-LA	21/105	956	663	0.420	–
5/20 SF/CH-LA	315	SF/CH-LA	21/84	956	671	0.450	–
5/25 SF/CH-LA	294	SF/CH-LA	21/105	956	668	0.450	–
5/30 SF/CH-LA	273	SF/CH-LA	21/126	956	665	0.450	–
5/25 SF/SG	294	SF/SG	21/105	956	678	0.450	–
5/30 SF/SG	273	SF/SG	21/126	956	677	0.437	–
Samples containing lithium nitrate							
Control at 0.5 Li/(Na + K)	420	–	–	956	690	0.450	12.5
Control at 0.74 Li/(Na + K)	420	–	–	956	690	0.450	18.4
Control at 1.0 Li/(Na + K)	420	–	–	956	690	0.450	24.9
Control at 1.5 Li/(Na + K)	420	–	–	956	690	0.450	37.4
Control at 2.25 Li/(Na + K)	420	–	–	956	690	0.450	56.1
20% FA at 0.5 Li/(Na + K)	336	FA: F-LA	84	956	667	0.436	10.0
20% FA at 0.74 Li/(Na + K)	336	FA: F-LA	84	956	667	0.436	14.8
20% FA at 1.0 Li/(Na + K)	336	FA: F-LA	84	956	667	0.436	19.9
20% FA at 1.5 Li/(Na + K)	336	FA: F-LA	84	956	667	0.436	29.9

[a] The RCA is composed of three equal parts of material between the 20 mm to 14 mm, 14 mm to 10 mm, and 10 mm to 5 mm sieves.
[b] Values of effective w/cm exclude correction due to absorption of aggregates and water from $LiNO_3$, if used.
[c] $LiNO_3$ used as solution of specific gravity = 1.20 and solid content of 30%.

in a major reduction in the expansion. Fig. 1 also shows that the expansion of RCA fine aggregate, tested with a non-reactive coarse aggregate exceeded the 0.04% ℓ/ℓ expansion limit at 1 year.

The effect of alkali loading or cement alkali content on the expansion of concrete prisms containing coarse RCA and those containing virgin Spratt aggregate is shown in Fig. 2. While PC of 0.70 wt.% Na_2O_e resulted in a 1-year expansion < 0.04% ℓ/ℓ for concrete prisms with Spratt, a PC of alkali content = 0.56 wt.% Na_2O_e did not reduce the expansion of concrete with RCA to below the 0.04% ℓ/ℓ limit.

Fig. 3 shows the accelerated mortar bar expansions of fine RCA produced initially by crushing the deteriorated concrete (primary crushing) and the expansion of crushed and sieved coarse RCA (secondary crushing). The aggregates produced by primary crushing are the same fine RCA tested in the CPT and shown in Fig. 1, while the secondary crushing represents the coarse RCA. The graph in Fig. 3 also includes the expansion of mortar bars containing the virgin reactive aggregate Spratt. The horizontal line on the graph represents the ASTM expansion limit of 0.10% ℓ/ℓ at 14 days (after 14 days of soaking in the alkaline solution or 16 days of casting). The graph shows that the AMBT was effective in evaluating the reactivity of the RCA tested in this study. The higher expansion of the secondary crushed RCA is probably attributable to its higher reactive aggregate content. Fine aggregate produced initially from the deteriorated concrete is expected to be composed mainly of weaker mortar rather than fractions of coarse aggregate. It should be noted that the same trend (higher expansion for coarse RCA) was obtained when fine and coarse RCAs were tested using the CPT (Fig. 1). The virgin Spratt aggregate showed the highest expansion in the AMBT. The possible reasons for this trend are presented in the Discussion section of this paper.

Fig. 4 shows the expansion of RCA and Spratt when tested using the CMBT. For the Spratt virgin aggregate, a suggested expansion limit 0.140% ℓ/ℓ at 30 days has been put forward for aggregate size from 4.75 mm to 12.5 mm [25]. Another limit of 0.093% ℓ/ℓ at 14 days has

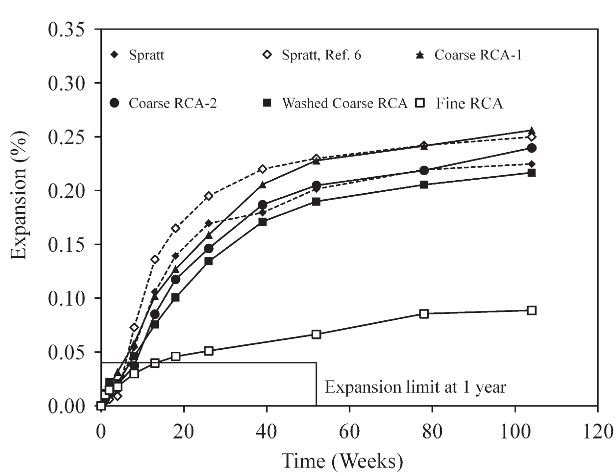

Fig. 1. Expansion of control samples containing Spratt, and coarse and fine RCAs.

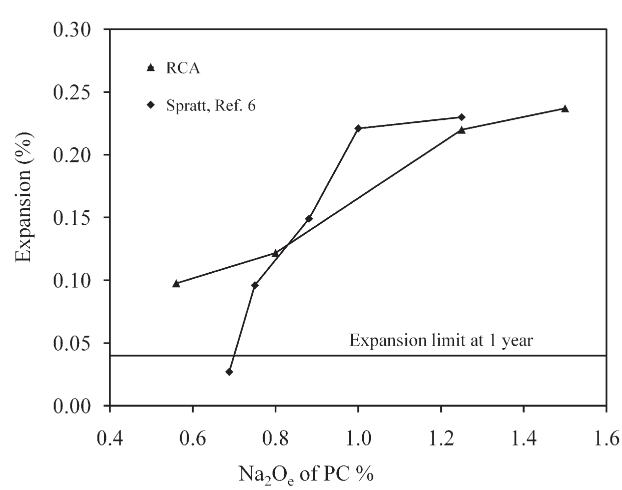

Fig. 2. Effect of alkali content of PC on the one-year expansion of concrete prisms.

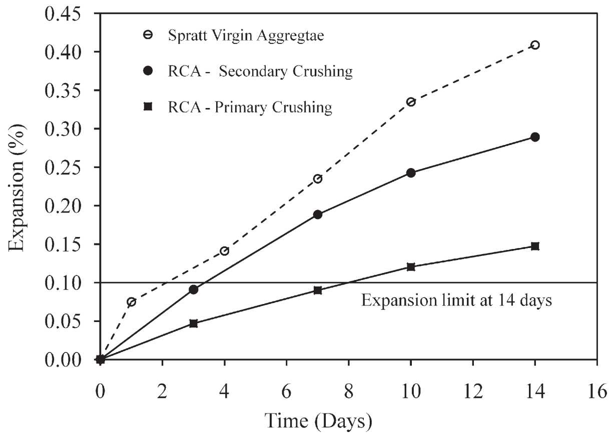

Fig. 3. Expansion of the RCA and Spratt in the AMBT.

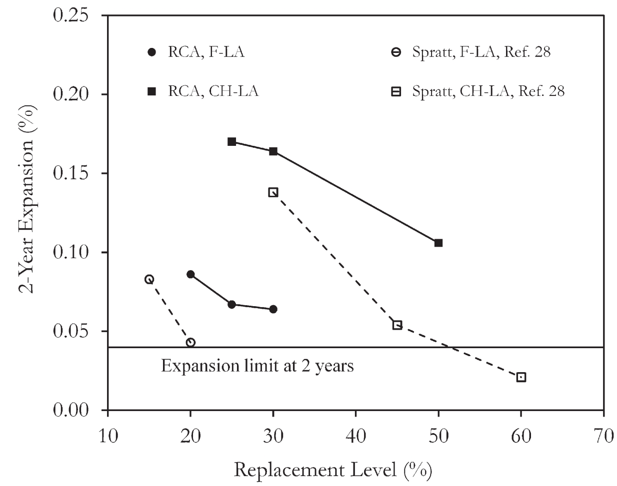

Fig. 5. Effects of types F and CH fly ash on expansion of concrete containing Spratt and RCA.

also been suggested for alkali–silica reactive aggregates; however, this limit is for 2.5 mm to 5.0 mm aggregate samples [26]. The expansion trend shown in Fig. 4 suggests that the test is promising in terms of evaluating the reactivity of RCA. However, a testing period of at least 28 days is required to better evaluate the reactivity of this type and size range of aggregate. Considering the suggested expansion limit of 0.140 ℓ/ℓ at 30 days [25] (or 28 days in this paper), it can be seen from the graph that using a size from 4.75 mm to 9.5 mm is better in terms of evaluating the reactivity of this aggregate. The 9.5 mm to 12.5 mm fraction showed a 28-day expansion value lower than 0.140 ℓ/ℓ at 28 days. Knowing that the 0.140% ℓ/ℓ limit was suggested for aggregates from 4.75 mm to 12.5 mm, the average expansion value of the two tested fractions (0.152% ℓ/ℓ) should be used along with the 0.140% ℓ/ℓ limit; this would classify the tested RCA as reactive. However, the use of CMBT for evaluating the reactivity of RCA and developing an appropriate expansion limit requires further investigations.

3.2. Preventive measures

The effects of different binary and ternary blends of SCM on the expansion of concrete with RCA and concrete with virgin Spratt are shown in Figs. 5 through 7. The expansion results for concrete with Spratt are obtained from an earlier study [28] using SCMs of similar chemical composition to those used with the RCA but not necessarily from the same sources. Fig. 5 compares the 2-year expansions of concrete containing Spratt with those of concrete containing RCA. It is clear from the graph that RCA requires higher levels of low and high-calcium fly ashes to mitigate the expansion, compared to the levels required for Spratt. Indeed, 50 wt.% CH-LA fly ash was enough to give a 2-year expansion below the 0.04% ℓ/ℓ expansion limit for concrete with Spratt, but more than 70 wt.% would be required to give the same level of expansion in concrete with RCA, as can be determined by extrapolating the curve in Fig. 5. The same can be said for all other SCMs including binary and ternary blends as shown in Figs. 6 and 7. In these figures the expansion of concrete containing Spratt and binary and ternary blends of slag and silica fume/slag is obtained from references [29] and [30], respectively. Fig. 6 shows that up to 12 wt.% SF was not enough to suppress the expansion in concrete with RCA but 10 wt.% was enough for concrete with Spratt. The results of ternary blends containing 5 wt.% SF and different levels of SCM are shown in Fig. 7 which also confirmed that RCA requires higher levels of SCM than Spratt to mitigate the expansion. The sample containing 5/25 SF/CI LA showed a relatively low level of expansion during testing. To confirm this result, an identical sample was prepared and tested. The 2-year expansions of these two samples were 0.041 wt.% and 0.038 wt.%. The average value of the two sets was plotted in Fig. 7.

Fig. 8 demonstrates that there is a reasonably good correlation between the 14-day expansion from the AMBT and the 2-year expansion from the CPT (or 1 year in case of the standard control

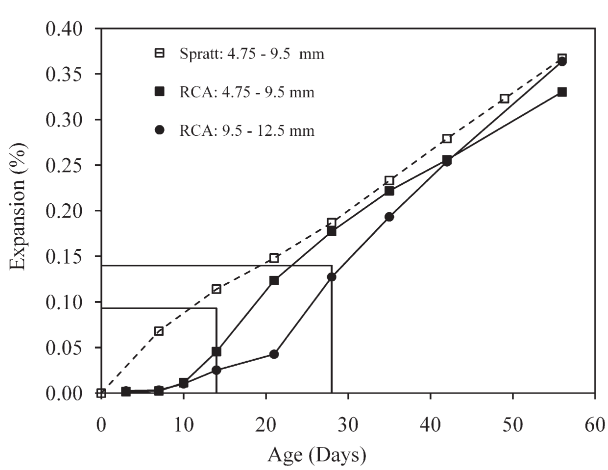

Fig. 4. Expansion of RCA and Spratt in the CMBT.

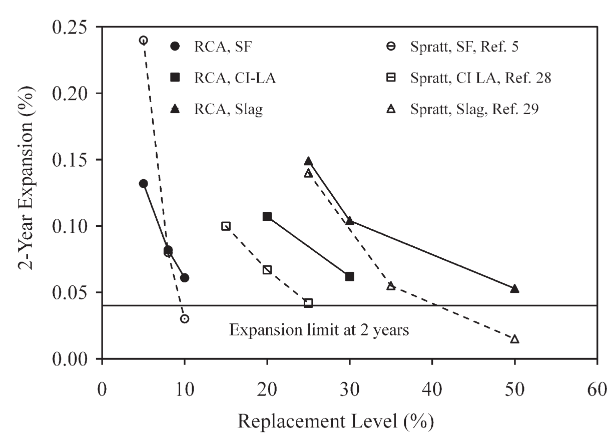

Fig. 6. Effects of SF, Slag and moderate-calcium, low-alkali fly ash (CI FA) on the expansion of concrete containing Spratt and RCA.

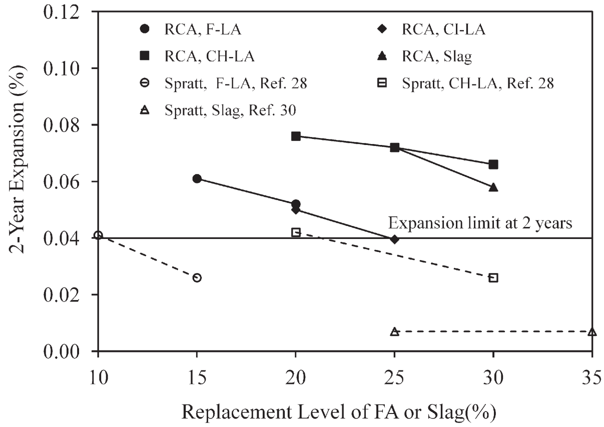

Fig. 7. Expansion of concrete with ternary blends of 5 wt.% SF and different levels of FA or Slag.

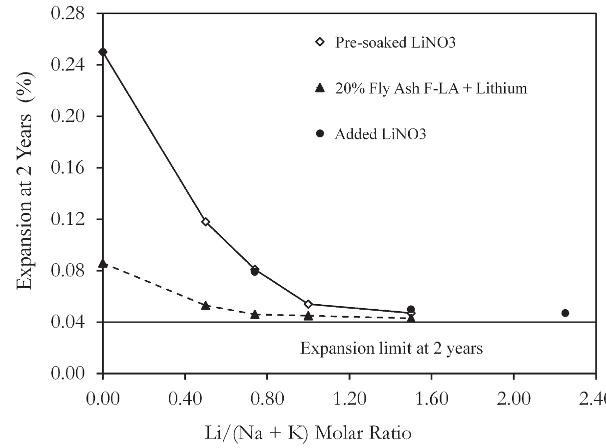

Fig. 9. Effects of lithium nitrate on the expansion of concrete with RCA at 2 years.

sample with no SCM). However, more testing is needed to see if the trend still exists for samples with CPT expansion lower than 0.04% ℓ/ℓ at two years. It should be noted that all the AMBT conducted in this study contained crushed coarse RCA or RCA produced from re-crushing the coarse RCA (secondary crushing).

Fig. 9 shows the expansion at 2 years of concrete prisms containing different levels of lithium nitrate expressed as Li/(Na + K) molar ratio of the alkalis in the mix, without considering the alkalis contributed from the RCA. Pre-soaking the aggregate in lithium solution and half the mixing water did not have much positive effect on mitigating the expansion. As Fig. 9 shows, all the tested dosages resulted in concrete expansion higher than the 0.04% ℓ/ℓ at the age of 2 years. However, there was a considerable reduction in the expansion compared with samples with no lithium. Fig. 9 also shows the expansion of concrete containing 20 wt.% low-calcium fly ash and different levels of lithium. There is an improvement in the mitigation when both materials are used together; however, the minimum achieved expansion at 2 years was 0.043% ℓ/ℓ.

3.3. Scanning electron microscopy investigation

Polished sections of RCA particles were examined using SEM to study some of the possible reasons behind the reactivity of RCA. The examination showed the particles to contain both gel-filled and empty cracks, as shown in Fig. 10. The effects of these features on the expansion are discussed under the Discussion section.

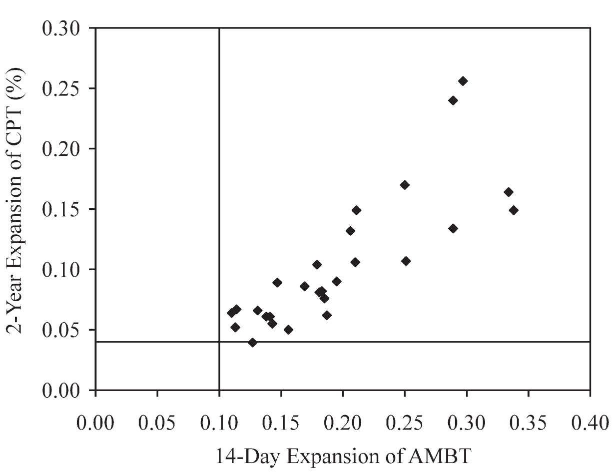

Fig. 8. CPT expansion at 2 years (1 year in case of the control sample) versus 14-day expansion of AMBT for samples with RCA.

4. Discussion

The results presented in Fig. 1 confirm that the ASR-affected RCA used in this study would produce significant levels of disruption if used in new concrete without appropriate preventive measures. The level of expansion would be similar, if not higher, than that produced in concrete containing the original virgin aggregate used in the RCA. The high expansion of concrete containing the RCA can be attributable to one or a combination of the following reasons: (1) the alkalis contributed from the residual mortar in the RCA, (2) expansion of the existing ASR gel in the RCA when exposed to high level of moisture in the new concrete, and (3) exposing new or fresh faces of the reactive

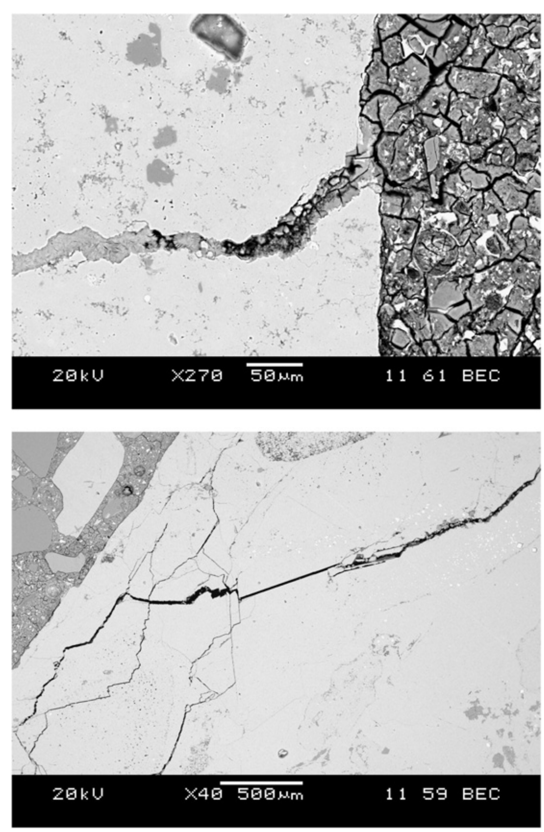

Fig. 10. BSE images showing coarse RCA particles with residual pastes. Top image shows ASR-gel filled crack in the Spratt aggregate. Bottom image shows empty cracks in Spratt particle which is believed to be resulting from crushing and processing of the old concrete.

virgin aggregate during crushing and processing of RCA. Examining RCA particles under the scanning electron microscope (Fig. 10) showed the presence of ASR gel within the Spratt reactive aggregate in RCA particles. The lower image in Fig. 10 also shows empty cracks within the Spratt aggregate in the RCA. These types of cracks were, most likely, produced during crushing and processing the old concrete to produce the RCA. It is possible that the presence of these cracks promotes more reaction and expansion in the new concrete by providing an easy access for alkalis to reaction sites within the aggregates. These cracks also increase the aggregate surface area that is exposed to alkalis, which promotes more reaction and expansion.

It was postulated that washing the RCA would wash out large amounts of alkalis from the residual mortar in the RCA and hence reduce the rate of reaction and expansion. The obtained high expansion value suggests that the 18 h of washing were not enough to wash out considerable amount of alkalis. Another possibility is that the alkalis might as well have been washed out but the effect may be overwhelmed by the attribution of fresh alkalis from the new paste. Same conclusion was drawn when 25 wt.% low-calcium fly ash was used with washed RCA. The reduction in expansion due to washing was insignificant. Indeed, the 2-year expansion was 0.066% ℓ/ℓ for unwashed RCA and 0.061% ℓ/ℓ for washed RCA.

Fig. 1 also shows that fine RCA produces less expansion compared to coarse RCA. This is attributable, most likely, to the lower reactive aggregate and higher residual mortar contents in the fine RCA produced during initial crushing of the old concrete. Other research work [31] has shown that using fine powder of reactive aggregate along with the same aggregate can reduce the expansion through the pozzolanic activity of the powder. Here, the pozzolanic effect of the fine RCA in reducing expansion is considered negligible. The fine RCA had a fine-aggregate gradation; in other words, the amount of powder or materials finer than 80 μm was very limited compared to the amount of powder investigated in reference [31]. In addition, the powder produced from siliceous limestone aggregate (of similar main composition to the Spratt contained in the RCA) was found to have the least reduction in expansion compared to the other tested aggregates, e.g. glass, quartzite and opal [31].

The authors believe that the alkalis contributed from RCA were the reason behind the higher expansion of concrete with RCA compared to that of concrete with Spratt when PCs of alkali contents <0.80 wt.% are used (Fig. 2). This trend did not continue at higher alkali contents. Indeed, the expansion of RCA-concrete was similar to that of the Spratt-concrete at PC of alkali content = 1.25 wt.%. This can be explained based on the behavior of the reactive aggregate under investigation (Spratt) which shows very little further expansion beyond an alkali content of 4.20 kg/m^3 of concrete or 1.00 wt.% Na_2O_e of the PC, as shown in Fig. 2 and reported elsewhere [6]. This is also the reason behind the similar expansion values obtained for RCA-concrete with PC of alkali contents of 1.25 wt.% and 1.50 wt.% Na_2O_e as shown in Fig. 2.

Since the main mechanism by which SCM reduces expansion due to ASR is by binding alkalis from concrete pore solution [6,7], one would expect that systems of higher alkali contents would require higher levels of SCM to lower the pore solution alkalinity to a "safe level". This indeed was the case in this study where the RCA required higher levels of SCM than virgin Spratt aggregate to achieve the same level of expansion, as shown in Figs. 5 to 7. The alkalis contributed from the residual RCA paste contributed to the total alkalis in the concrete mixtures. Scott and Gress [16] also found that higher levels of SCM were required to mitigate expansion in concrete containing RCA with fine-grained quartzite aggregate.

An interesting observation, though, is that the Intermediate Calcium (CI-LA) fly ash used in this study achieved better results than the Low-Calcium (F-LA) ash. This could be attributable, at least partly, to the higher fineness of the CI ash used in this study compared to the F ash (14.9 wt.% versus 26.7 wt.% retained on 45 μm-sieve for CI and F ashes, respectively as listed in Table 1). In addition, earlier research work [6] has shown that Low and Intermediate Calcium fly ashes (up to CaO content of 20 wt.%) perform more or less equally in terms of resisting ASR, as long as their alkali contents are similar.

The results showed that the AMBT can be used to evaluate the reactivity of RCA and the efficacy of SCM as preventive measures. The same finding has been reported in other research work for natural reactive aggregate tested with different blends of SCM [6,29]. Although more testing is needed to see whether or not samples that pass the CPT also pass the AMBT, the fact that none of the samples tested in this study passed the 0.10% ℓ/ℓ expansion criterion of the AMBT and failed that of the CPT (0.04% ℓ/ℓ) provides some comfort that the AMBT does not underestimate the expansion of concrete prisms (Fig. 8). It is very important, however, to make sure that the RCA tested in the AMBT is representative of the RCA under investigation. In other words, when evaluating coarse RCA, it is important to make sure that processing the aggregate to obtain the required gradation for AMBT is done in a manner that does not significantly change the ratio of coarse aggregate to residual mortar in the RCA under investigation. Indeed, if processing coarse RCA produces a sample that mainly consists of residual mortar, the expansion of the AMBT will be low and underestimate the expansion of the coarse RCA when used in CPT or actual structures. While this has not been the case in this study, more testing should be conducted on RCA of different properties prior to recommending the AMBT as a tool for evaluating the reactivity of RCA and the efficacy of preventive measures. One way of avoiding excessive processing of coarse RCA is to use the concrete microbar test as accelerated test. The test allows using aggregate size that is much larger than that used in the AMBT. This may help in testing samples that are more representative of the coarse RCA under investigation. While the concrete microbar results obtained in this study were promising, more investigation is needed in this area.

The reason for the Spratt aggregate to produce higher expansion than RCA in the AMBT (Fig. 3) is attributable to the fact that the bars in case of Spratt contained higher amount of reactive silica. This is because the aggregate particles consisted only of reactive aggregates with no residual mortar. Unlike the case with CPT, the alkalis contributed from the residual mortar of the RCA did not seem to have significant impact on the expansion as the effect of these alkalis is masked by the abundant supply of alkalis from the soaking solution.

Lithium nitrate has shown high efficacy in mitigating expansion due to ASR in both new and in-service concrete. One of the mechanisms suggested by Kurtis et al. [14] is that some lithium salts may prevent repolymerization of the gel. Lithium was used in this research with the idea that it would stop any further repolymerization and expansion, if any, of the existing ASR gel, and prevent the formation of new expansive gel. The recommended dose of lithium in molar ratio of Li/(Na + K) in the mix is in the range of 0.74 to 1.1 wt.% [12,13]. The measured total alkali content of the RCA was found to be 0.56 wt.% Na_2O_e. However, this value includes all the alkalis not only those available to the concrete pore solution. If we assume that all the alkalis are available, then the concrete would have around 2.25 times the alkalis load contributed by the Portland cement. In this case, the adequate lithium dose would be ≤2.25 times the recommended dose based on the alkalis from PC. The results in Fig. 9 showed that a Li/(Na + K) molar ratio up to 2.25 was not enough to suppress the expansion in concrete with RCA, although the reduction in expansion was significant. The graph in Fig. 9 also shows that increasing the Li/(Na + K) ratios beyond 1.5 did have significant benefit on mitigating the expansion. Combination of lithium and low-calcium fly ash showed lower expansion than samples with fly ash or lithium alone; however, the lowest expansion at 2 years was 0.043% ℓ/ℓ. It is also worth noting that for samples with 20% fly ash, an increase in lithium solution beyond a Li/(Na + K) ratio of 0.74 did not produce significant reduction in the expansion.

The observed low efficiency of common preventive measures to maintain the expansion below 0.04% ℓ/ℓ at 2 years suggested that there may be other mechanisms that contribute to the expansion of the samples. Knowing that RCA contains residual mortar, swelling of the mortar when exposed to high humidity could add to the expansion. This was investigated by testing two commercial non-reactive RCAs using the concrete prism test. The two samples obtained expansion values of 0.031% ℓ/ℓ and 0.035% ℓ/ℓ at 1 year. The contribution of swelling of RCA to expansion was also reported in another study [16]. Since the tested non-reactive RCAs were, most likely, of different composition than the reactive RCA investigated here, the level of swelling of the latter is expected to be different. However, it is likely that part of the obtained expansion with reactive RCA is due to swelling of the residual mortar. If it is desired to keep the total expansion, regardless of the cause, below 0.04% ℓ/ℓ at 2 years, then it should be kept in mind that very effective preventive measures are needed such as adequate levels of ternary blends of silica fume and low or moderate-calcium fly ash.

It should also be mentioned that when RCA is used in concrete, it is usually blended with natural coarse aggregates. With the use of less amount of reactive RCA per unit volume of concrete, lower expansion may be obtained using moderate levels of preventive measures. This is currently under investigation at Ryerson University.

5. Conclusions

1. RCA produced from ASR-affected concrete after 12 years of site exposure was found to be as reactive as the original aggregate used in the mix which was a reactive siliceous limestone (Spratt).
2. The RCA required higher levels of SCM to mitigate the expansion than those required by the original reactive aggregates used in the old mix.
3. Fine RCA produced by primary crushing of concrete is less reactive than the coarse RCA. This is attributable, most likely, to the high residual mortar, or less reactive constituents, in the fine aggregates.
4. For the RCA investigated in this study, it was found that the concrete prism and the accelerated mortar bar tests were effective in evaluating the reactivity of RCA as well as the efficacy of SCM as preventive measures. It should be emphasized that the accelerated mortar bar test should be performed on samples that are representative of the coarse RCA under investigation. Extra care is needed during crushing and screening of the coarse RCA.
5. Lithium nitrate was effective in reducing the expansion of concrete containing RCA but the range of dosages used in this study did not suppress the expansion to the allowable limit.
6. Swelling of the residual mortar in RCA is believed to contribute to the obtained expansion of concrete with reactive RCA.

Acknowledgements

This research project is funded by a grant from the Ontario Ministry of Transportation (MTO) under the Highway Infrastructure Innovation Funding Program, and a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). The financial support of both organizations is highly appreciated. Opinions expressed in this paper are those of the authors and may not necessarily reflect the views and policies of the Ministry of Transportation of Ontario.

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