Matthew Piersanti, Medhat H. Shehata, A study into the alkali-silica reactivity of recycled concrete aggregates and the role of the extent of damage in the source structures: Evaluation, accelerated testing, and preventive measures, Cement and Concrete Composites, 129, 2022, 104512, ISSN 0958-9465, https://doi.org/10.1016/j.cemconcomp.2022.104512

A Study into the Alkali-Silica Reactivity of Recycled Concrete Aggregates and the Role of the Extent of Damage in the Source Structures: Evaluation, Accelerated Testing, and Preventive Measures

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Highlights

- Depending on its source, RCA causes higher or similar expansion as natural aggregates
- Cores from deteriorated elements expanded less than concrete samples containing RCA.
- Silane-based sealers reduced expansion slightly but did not prevent it.
- RCA requires more SCM to mitigate expansion compared to natural reactive aggregates
- The Accelerated test methods were effective in evaluating the reactivity and efficacy of SCM

Abstract

This paper covers the expansions of new concrete containing recycled concrete aggregates (RCA) produced from bridge barriers suffering different levels of damage due to alkali-silica reaction (ASR). RCA sourced from high-deterioration concrete produced a higher expansion than natural aggregate or RCA from low-deterioration concrete, although the difference is not high. The expansion of lab-prepared cylinders with RCA was higher than that of cores extracted from the old concrete elements. The standard accelerated mortar bar test (AMBT) and a modified version thereof customized to accommodate RCA's properties, including high absorption, was effective in predicting the expansion of concrete prisms containing natural reactive aggregates or RCAs cast with different cementing blends. Also, the Concrete Micro Bar Test used with suggested expansion limits at 28 and 56 days was found effective in predicting the expansion of concrete prisms at one or two years for samples with and without preventive measures.

Keywords: Recycled concrete aggregate; alkali-silica reaction; concrete prism test; extracted cores; accelerated mortar bar and concrete microbar tests; silane-based sealer and preventive measures

1 Introduction

When a concrete element reaches the end of its service life, it is demolished and placed in landfills. Reusing demolished concrete as recycled concrete aggregate (RCA) in new concrete mixtures helps reduce the amount of waste generated by replaced concrete structures. However, RCA needs testing to determine its usability as an aggregate in new concrete. The original aggregate used in the demolished structure has a major impact on the RCA usability, and different precautions may need to be taken. For instance, an RCA produced from a structure that has suffered alkali-silica reaction (ASR) may continue to cause expansion if used in a new structure without preventive measures [1-9]. In reality, more than one deterioration mechanism is likely co-occurring. As one

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deterioration mode begins to attack a structure, the concrete becomes more susceptible to other deterioration modes, increasing deterioration [10].

Alkali-silica reaction is a deterioration mechanism that causes severe expansion and disruption in concrete. The reaction requires the presence of (i) reactive silica found in some aggregates, (ii) alkalis which are usually available in concrete pore solution, and (iii) humidity [11]. The hydroxyl ions accompanied by K^+ and Na^+ dissolve the reactive silica from the aggregate, combining with calcium to form an ASR gel. Upon absorbing moisture, the ASR gel swells and expands. This expansion - starting within or around the aggregate - causes an increase in pressure, which inevitably causes the concrete to crack [11-13]. Alkali-silica reactive aggregates can be used in concrete with the mitigation methods such as the incorporation of supplementary cementing materials (SCM) [12-16] or the use of surface treatment such as sealers [17]. When using SCM, it is imperative to use sufficient levels to reduce the expansion below the specified expansion limit [20]. The efficacy of SCM varies from one type to another [13-16]. Silica fume used as the sole SCM at low replacement levels (e.g., 5%) may reduce expansion at early ages but might not be effective in the long term [12,14]. High-alkali SCMs are less effective in mitigating the expansion than SCMs of low alkali content [12,13,15]. Also, high calcium fly ash is less effective than low calcium fly ash in mitigating the expansion [12,13]. In terms of using sealers, a silane-based sealer applied to concrete barriers was found to reduce the cracking over a period of ten years [17]. The sealer was able to stop the expansion for six years when applied to severely affected barriers and longer when applied to moderately deteriorated barriers [17].

RCA produced from concrete suffering ASR was found to cause significant expansion when used as aggregate in lab-prepared concrete prisms [1-9]. The expansion of concrete prisms with a natural reactive limestone (Spratt) from Ottawa, Ontario, was slightly lower than new concrete prisms made with RCA containing the same reactive aggregate [2]. Other studies [3,4] showed the opposite trend, with RCA producing less expansion than the natural aggregate. The reactive RCA required higher dosages of SCMs - compared to those required by the natural stone - to mitigate the expansion [2,6,20-22]. Using the reactive RCA as partial replacement of the coarse aggregate in concrete was found to reduce the expansion [4, 6, 20] and require lower levels of mitigation, compared to using the RCA as a total replacement of the coarse aggregate [20]. Although high levels of SCM - including ternary blends of silica fume and fly ash - were necessary to reduce the expansion in Spratt-RCA below the 0.040% limit at two years [2,20], this may not be the case for other types of RCA. Factors such as alkali-contributed by RCA and reactivity of the aggregate govern the level of SCM required for mitigation. The effect of level of expansion and damage in the recycled concrete was found to affect the reactivity of the RCA [3,4]. In one study, RCA produced from concrete suffering more damage was less expansive, which was attributed to the lower level of remaining reactive silica [4]. In the other study, RCA from more damaged concrete showed slightly higher expansion [3].

In terms of aggregate reactivity, Shehata and Thomas [23] compared two aggregates from Ontario - Spratt (siliceous limestone) and Sudbury (reactive gravel) - and found that Spratt requires less alkali content to expand compared to Sudbury. For example, concrete prisms containing Spratt aggregate and Portland cement (PC) of 0.70% Na_2O_e expanded beyond the acceptable limit. In contrast, concrete prisms with Sudbury aggregate did not expand when used with the same Portland cement (PC). One would expect that Sudbury aggregate or RCA containing Sudbury aggregate may require less SCM to maintain the expansion below a certain level. This was found in the preliminary work of Piersanti et al. [24].

In terms of testing, the Concrete Prism Test (CPT) [25] has been used to evaluate the reactivity of natural aggregate and RCA, and the efficacy of SCM [2,12-16], although alkali leaching has been reported as a major issue of this test [13]. The accelerated mortar bar test (AMBT), as described by Adams et al. [26], has also been used with modifications to correct for RCA absorption and make sure the processed aggregate is representative of the coarse RCA and contain a similar proportion of original stone and residual mortar as the coarse RCA [2,22,26,27]. The importance of taking the RCA absorption into consideration when running the AMBT was also reported in other research work [8]. In some cases, the AMBT underestimated the expansion compared to CPT [6]. The Concrete Microbar test (CMBT) [28] was used to evaluate the reactivity of aggregate [29,30,31]. Grattan-Bellew et al. [29,30] suggested different expansion limits depending on the aggregate composition. The suggested expansion limit ranged from 0.09% [30] to 0.14% [29] at 30 days for siliceous limestone, and 0.04% [30] to 0.05%[29] for other reactive aggregates. Lu et al. [31] evaluated the test using different aggregate sizes where they found the size from 2.5 mm to 5.0 mm to produce the best correlation with the concrete prism test results. Shehata et al.[2] and Johnson and Shehata [27] reported limited data on the use of the test with RCA with sizes ≥ 5 mm and found a good correlation with concrete prisms for samples with and without SCM. Besides mortar and concrete tests, a petrographic procedure was used to identify the reactivity of fine RCA, and the results were confirmed using the AMBT [9].

The work in the literature covers the reactivity of a variety of RCA sources with different levels of damage as evaluated by CPT or AMBT, without much work on preventive measures or the use of CMBT. Some research works related the expansion in new concrete to the level of the damage in the source concrete [3,4] with some level of contradiction. Since the reactivity of RCA is related to its source, this study adds to the literature on the effect of level of damage on the reactivity of RCA. In addition, this study compares the expansion of new concrete with RCA produced from concretes of different levels of damage to that of cores extracted from the source concrete and tested under lab conditions, with and without silane coating. The expansion of new concrete with RCA was compared to cores - with and without silane coating - to help explain the reactivity of RCA based on the availability of the three ASR essentials: alkalis, reactive silica, and moisture.

In terms of testing, most of the available studies investigated the standards CPT or a modified version of AMBT. This study investigates both in addition to the concrete microbar test (CMBT) with and without SCMs. Compared to CPT, the CMBT has the advantage of a shorter test duration. Compared to AMBT, the CMBT has the advantage of testing coarse aggregate without further processing the RCA to sand size. If not done correctly, the processing of coarse RCA to fine fractions can produce unrepresented samples with residual mortar content different than the coarse RCA, producing unreliable results. There has been some evidence in the literature that the AMBT might provide lower expansion results compared to CPT [6, 27]. Moreover, some sandstones provide false negatives when tested using the AMBT [32]. These facts suggest that an accelerated test, such as the CMBT, is in need in cases where the AMBT is not the best option. Data on the CMBT is needed to examine its suitability for evaluating the expansion and efficacy of preventive measures. An earlier study by the same research team [27] presented data on CMBT using a reactive siliceous limestone (Spratt) with and without preventive measures. In this study, RCA containing reactive gravel and the original coarse aggregate were tested to add to the data. It was thought that a modification or a confirmation of the proposed expansion limit is likely to be needed based on the new data, which is investigated here. In addition, different types and levels of SCM were tested here with both reactive RCA the reactive natural gravel used in the source concrete.

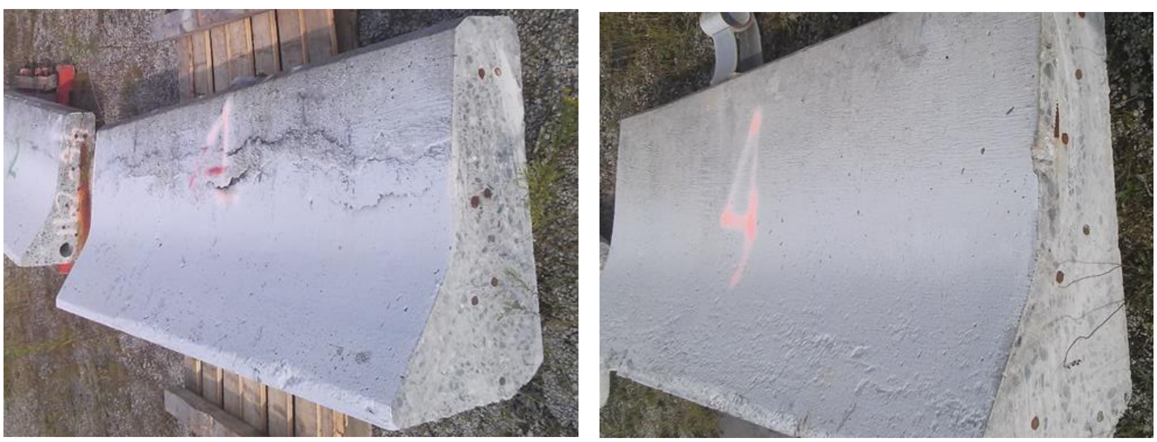
Testing SCM with both RCA and the virgin aggregate using the two accelerated tests (AMBT and CMBT) and comparing them to the results of the CPT provides insights into the potential use of each of the tests. The combined results from the earlier study [27], other studies on CMBT [29,30], and the current study are discussed, and a modified two-steps expansion limit is proposed. This paper also investigates the effect of silane on mitigating the expansion on extracted cores and concrete prisms and cylinders containing RCA.

2 MATERIALS AND EXPERIMENTAL DETAILS

2.1 Materials

2.1.1 Aggregate and Cementing Materials

The RCA used here was obtained from road barriers of a bridge in Sudbury, Ontario. The barriers contain a reactive coarse aggregate from Sudbury, Ontario, Canada. When collected, the road barriers were over 20 years of age and contained Sudbury coarse aggregate, reactive gravel containing argillite, greywacke, and quartz-wacke. These road barriers suffered different degrees of deterioration due to ASR and freezing and thawing. The barriers were divided into two groups, classified as high deteriorated and low deteriorated barriers, as shown in Fig. 1(a) and Fig. 1(b).



(a) (b)

Fig. 1. (a) High deteriorated barrier and (b) low deteriorated barrier

RCA was reclaimed, and cores were extracted from the low and high deteriorated barriers. The Dry Bulk Relative Density (BRD) and absorption were tested in the lab for both Sudbury and Sudbury-RCA aggregates. The BRD for Virgin Sudbury aggregate was found to be 2674 kg/m^{3,} and the absorption was 0.54%, while Sudbury RCA had a BRD of 2359 kg/m^3 and absorption of 3.87%. The RCA is split into three categories: Sudbury-RCA, Sudbury RCA-H, and Sudbury RCA-L, with the letters H and L referring to high and low deterioration, respectively. In other words, the three types of RCA are: (i) Sudbury-RCA, which contains a mix of RCA collected from both high and low deteriorated barriers, (ii) Sudbury RCA-H, which contains RCA obtained from just high deteriorated barriers; and (iii) Sudbury RCA-L contains RCA obtained from just low deteriorated barriers. The relative content of high and low deteriorated RCA in Sudbury-RCA is unknown. A sample of the RCA can be seen in Fig. 2, showing the typical composition of RCA: (a) original stone (Sudbury) and (b) residual or old mortar. Only coarse RCA - 20 mm to 5 mm - was used here.

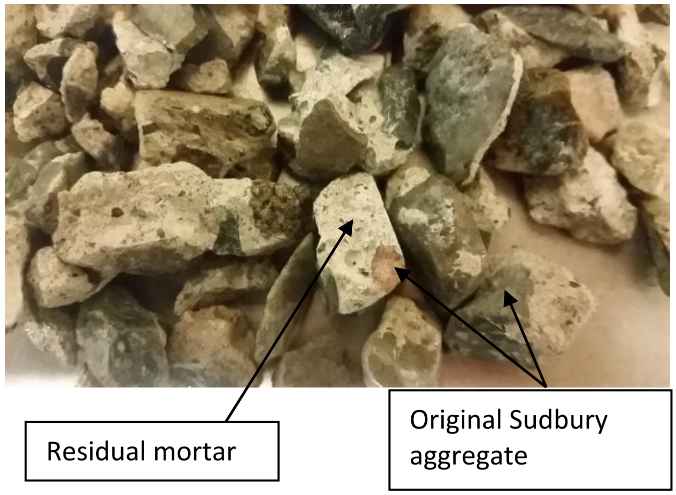


Fig. 2. Coarse RCA particle showing original stone and residual mortar

General Use Portland cement (GUPC), Silica Fume Blended Cement (HSF), Granulated Blast Furnace Slag (Slag), and High Calcium Fly Ash (HCFA) were used to prepare new mixtures with RCA. The chemical composition of the cementing materials determined by X-Ray fluorescence (XRF) is listed in Table 1.

Table 1. Oxide composition of the GUPC and SCM determined by XRF (Mass%)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Na_2O_e	Loss on Ignition	Total
GUPC	19.33	5.25	2.42	62.77	2.35	4.03	0.24	1.14	0.99	2.36	99.89
HSF	26.3	4.69	2.15	56.06	2.06	4.02	0.2	1.13	0.94	2.61	99.22
HCFA	34.01	18.35	6.32	26.41	6.09	1.39	1.71	0.61	2.11	2.42	97.31
Slag	36.9	7.82	0.68	39.9	11.2	0.45	0.59	0.74	1.1	1.96	100.24

2.1.2 Mixtures

Two concrete mixtures are used in this study: (i) a Standard Mix and (ii) a Bridge Mix. The main difference between them is the cement content. The standard mix was made in accordance with the standard method of Concrete Prism Test (CPT) [25] with a PC content of 420 kg/m^3 with the Na_2O_e of the PC raised to 1.25% using NaOH pellets. The Bridge Mix was made with 360 kg/m^3 of PC to mimic the mix believed to be used to build the damaged barriers. The bridge mix was mainly used to compare the expansion of new RCA concrete to cores extracted from the barriers. In addition to the concrete mixture, mortar [26] and microbars mixtures [28] were also prepared and tested, as will be explained in the coming paragraphs.

2.1.3 Silane-based sealer

A silane-based sealer was used to investigate its effect on reducing the expansion of both extracted cores and lab-prepared samples.

2.2 Experimental Details

2.2.1 Extracted Cores

Cores were extracted from high and low deteriorated barriers and placed in sealed bags until they were ready for testing in the lab. Before testing began, an apparatus was made using steel tubing, angle iron, and set screws to drill holes into the top and bottom of the cores. These holes were drilled using a drill press, and measuring studs were placed into the drilled holes and secured with non-shrink grout. In total, 6 high deteriorated and 6 low deteriorated cores were tested, in which 3 of each type have been coated with silane-based sealer. The silane coating was carried out as per subsection 2.2.4. The cores were tested under the same conditions of the CPT [25], which include storing above water (100% relative humidity) at 38°C. The length change was calculated as per CSA A23.2-14A [25]. However, instead of the traditional length comparator used for concrete prisms, the measuring device used was a micrometer of precision of 0.0025 mm. The expansion of the cores was monitored to (i) determine if the level of damage occurred in the structure has an effect on the residual expansion, (ii) to compare core expansion to expansion of samples cast with recycled aggregates and tested under the same conditions, and (iii) to determine the effects of silane-based coating on the progression of ASR.

2.2.2. Lab-Prepared Cylindrical Samples

To be able to compare residual expansion in extracted cores to the expansion of concrete with RCA produced from the same old concrete, cylindrical concrete samples (100 by 200 mm) were prepared. Since testing cylinders for expansion is not a normal practice, moulds that allow the placement of measuring studs are not commercially available. Thus, moulds were made so that measuring studs could be embedded into the top and bottom of the cylinders. Details of the moulds and sample preparation can be found in [33]. Each investigated concrete mixture consists of six cylinders: three treated with silane and three without silane. The conditioning and application of silane are described in subsection 2.2.4. In addition, the expansion results of the cylinders were compared with those from the concrete prisms to evaluate the change in expansion due to the geometry of the sample.

2.2.3 Concrete Prism Test

The CPT was carried out as per CSA A23.2-14A [25]. The mixtures were prepared at a 60:40 ratio of coarse-to-fine aggregate and a 0.45 water-to-cementing materials (w/cm) ratio. The alkali content of the mixtures was raised to 1.25% Na_2O_e per mass of PC. However, curing was done differently to enable treating companion samples with silane-based sealer, as described in subsection 2.2.4. The RCA aggregate was not washed in order to prevent leaching of alkalis from residual or adhered mortar in the particles. After the curing method described below, the buckets were placed in a room maintained at 38°C, and length readings were taken periodically as per CSA A23.2-14A [25].

2.2.4. Conditioning and Application of Silane-Based Sealer

For each set of extracted cores, cylinders, or prisms tested in the lab under the conditions of the CPT, a second set treated with a silane-based sealer was tested under the same conditions. For the prisms and cylinders, the zero readings were taken after demoulding and then placed in a bucket over water at room temperature for 14 days for the samples to gain some maturity and enough level of water saturation before the application of silane. After 14 days, silane was applied with a brush in two layers over two days, as per the guidelines of the silane producer. The samples were then kept in the air for 7 days. To compare expansion results, the samples that did not receive silane treatment went through the same 14-day curing and 7-day drying procedure. After the 21 days of curing and conditioning, the samples were stored above water at 38°C, and expansion was measured periodically as per standard CPT procedures.

2.2.5. Accelerated Mortar Bar Test

The test was carried out following the procedures described by Adams et al. [26]. The procedure is similar to the standard AMBT test method [34], but it incorporates a moisture correction for the high absorption of RCA [2, 26, 27].

2.2.6. Concrete Microbar Test

The concrete microbar test was used as per RILEM [28] to compare expansion produced using natural (or virgin) Sudbury and Sudbury-RCA. In the current study, the concrete microbars were cast using two coarse aggregate sizes: (i) 4.75 mm - 9.5 mm and (ii) 9.5 mm - 12.5 mm for both Sudbury and Sudbury-RCA. After finding out that the smaller size produces higher expansion, samples made with SCM (for both RCA ad Sudbury) adopted the small size aggregates (4.75 mm - 9.5 mm). The mixtures were cast at a water-cement ratio of 0.33 (with absorption corrections in the case of RCA) and a 1:1 cement-aggregate ratio. The length of the specimens was differed from the RILEM AAR-5 standard [28] to fit a standard North American gauge length of 280 mm rather than the 160 mm length described in the RILEM method. The alkali content was raised to 1.5% Na_2O_e per mass of PC using NaOH added to the mixing water. After standard curing for 24 hours, the bars were placed in water at 80ºC for 24 hours before being placed in 1 N NaOH solution at 80°C for 56 days. Readings were taken per RILEM [28] until day 28 and once a week until day-56.

2.2.7. Scanning Electron Microscopy:

Samples of recycled aggregate particles were examined under a scanning electron microscope (SEM) and Energy Dispersive Spectroscopy (EDS) analysis. The RCA particles were dried under vacuum, followed by being impregnated with epoxy. The samples were then polished using a 0.3 μm diamond grade and sputtered with carbon using Edwards Vacuum Coating System. The polished sections were examined under a JEOL JSM-6380 LV scanning electron microscope operated at 20 kV in backscattered electron imaging (BSE) mode.

3. RESULTS AND DISCUSSION

3.1. Characterization of Damaged Concrete and Recycled Concrete Aggregates

Fig. 3 shows extensive ASR gel in a concrete piece collected from the deteriorated barrier. The ASR gel could be seen by naked eyes reflecting the extensive damage in the barriers.

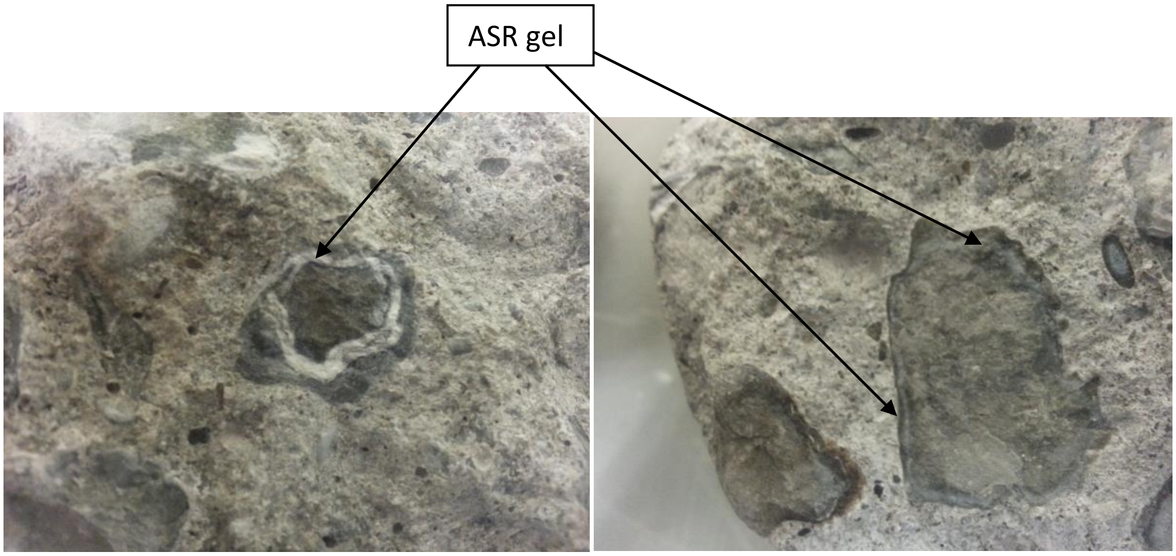


Fig. 3. ASR reaction product (gel) within the deteriorated concrete.

Fig. 4 shows a BSE image of RCA particle obtained from a high deteriorated road barrier showing a cracked stone filled with ASR product identified by EDS. The ASR product consists mainly of potassium, a high level of silica, and relatively low calcium, with Ca/Si of around 0.25. As discussed in the coming subsections, the presence of ASR products demonstrated in Fig. 3 and 4 could contribute to the high expansion of the concrete cast with RCA, especially RCA-H.

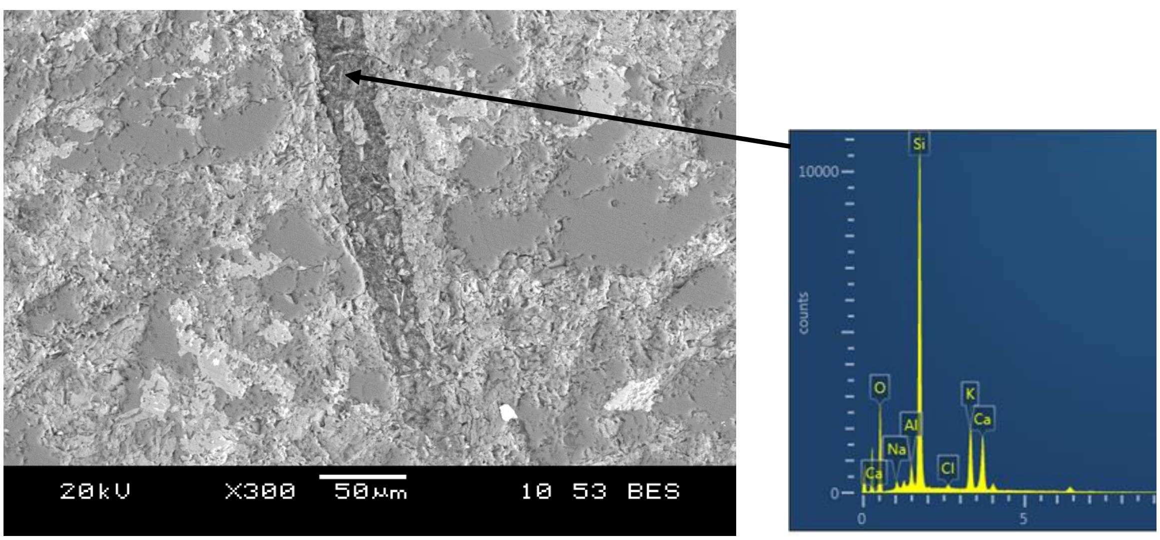


Fig. 4. SEM image of high deteriorated RCA particle (RCA-H) showing a crack in the original stone filled with ASR product as confirmed by the EDS spectrum

3.2. Expansion of Extracted Cores and Efficacy of Silane

Cores collected from low deteriorated barriers expanded at a higher rate than the high deteriorated cores, shown in Fig. 5. Each point on the graph is the average of three cores, with the error bar representing the standard deviation. The coefficient of variation (COV) at 52 weeks is listed on the graph for each data set. The low-deteriorated cores showed higher variability than the other samples, perhaps due to different levels of deterioration within the three tested cores. The high variability for the low deteriorated cores became more noticeable at 26 weeks and beyond. The reason is that the expansion of one of the three tested cores reached a plateau, contrary to the other two cores, which continued to expand, still with different values. However, the minimum expansion value in low deteriorated cores (0.074%) is still higher than the max value obtained in high-deteriorated cores (0.052%).

The expansions in the untreated and the silane-coated cores demonstrate that the expansion in the original concrete is still in progress. The reduced expansion in the silane-treated cores shows the expected role of moisture in promoting the expansion. However, testing treated and untreated cores did not confirm if the expansion was due to the formation of more reaction products or swelling of the existing ASR gel. In terms of alkali content in the barriers, concrete from both barriers showed similar alkali content ($Na^+ + K^+$) in an earlier study [35]. The Na_2O_e of the high and low deteriorated cores was determined experimentally to be 0.43% and 0.41% for high and low deteriorated barriers, respectively. The alkalis were determined by soaking samples in lime-saturated water and measuring the alkali-cations in solution after 7 days of agitation at 38 ºC. The K^+ and Na^+ in solution are used to calculate the Na_2O_e, assuming that the K^+ and Na^+ are associated with OH^- ions, and cement content of 360 kg/m^3 of concrete [35]. Hence, the high expansion in the low-deteriorated cores could be due to more unreacted sites, or perhaps the excessive cracking within the high deteriorated cores allowed the gel produced from ASR to divert to, causing less expansion.

A silane-based sealer was applied to a set of all cores types to determine if it is a sufficient mitigation method for ASR in deteriorated concrete and examine the role of moisture on continued reaction. The expansion in the high and low deteriorated cores was found to be reduced by 0.005 and 0.019 percent points, respectively, as shown in Fig. 5. The values are equivalent to 10% and 20% of the expansions without silane at one year, respectively. In other words, the silane looks to be more effective in the case of low-deteriorated concrete. A possible reason for the low silane efficacy in the case of high-deteriorated cores is the large number of surface cracks that might not have been bridged or covered by the silane, allowing water to intrude the sample. It should be kept in mind that the expansion of the high-deteriorated cores was low in the first place. On the contrary, when applying the silane to the low deteriorated cores with limited surface cracks, the silane effectively covers the entire surface of the cores and reduces water intrusion. However, the rate of expansion in the last three months showed an increasing trend, suggesting that the obtained expansion during the testing period and its associated cracks had allowed more moisture to penetrate the samples, causing an increased rate of expansion.

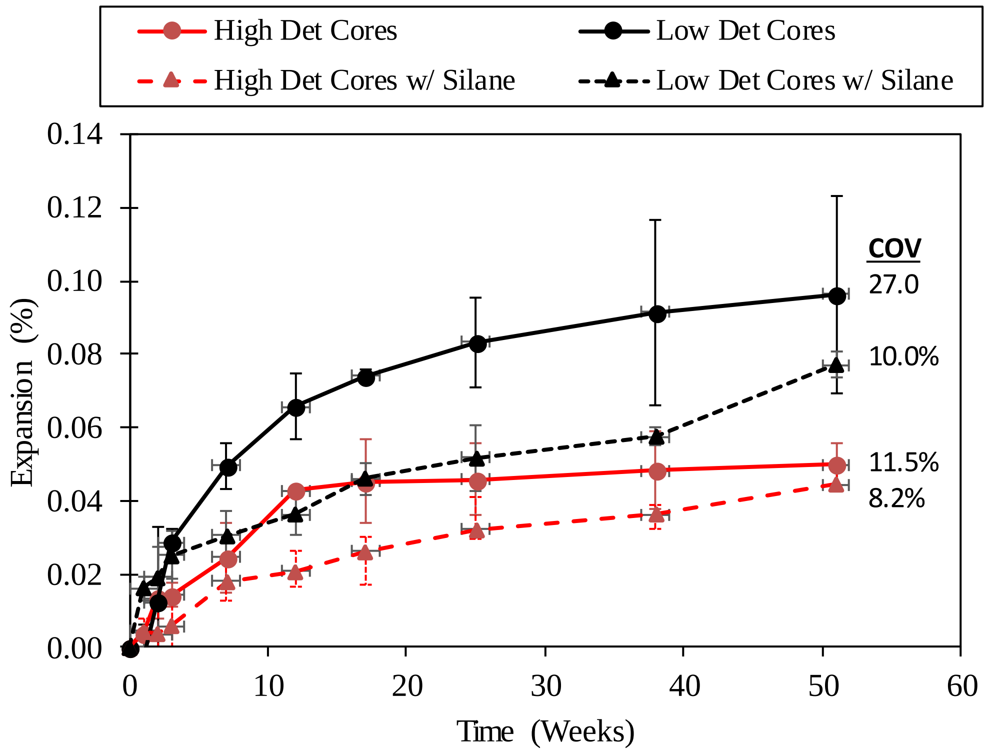


Fig. 5. Expansions of high and low deteriorated cores with and without silane. The error bars represent one standard deviation. The coefficients of variation (COV) are at 52 weeks (one year)

3.3. Expansion of Lab-Prepared Concretes and Efficacy of Silane

Lab data was collected for 52 weeks using the CSA standard procedures for the CPT [25] to compare results of the virgin Sudbury aggregate, high deteriorated RCA, and low deteriorated RCA in concrete prisms. In addition, cylinders were also cast, as mentioned earlier - with the same geometry as cores - to compare the results with those obtained from extracted cores. Fig. 6 shows the expansion of the three aggregates in the standard mixture containing 420 kg of cement per m^3 of concrete (420 kg/m^3 with alkalis boosted to 1.25% Na_2O_e) and the bridge mixture (360 kg/m^3) for concrete prisms and cylinders.

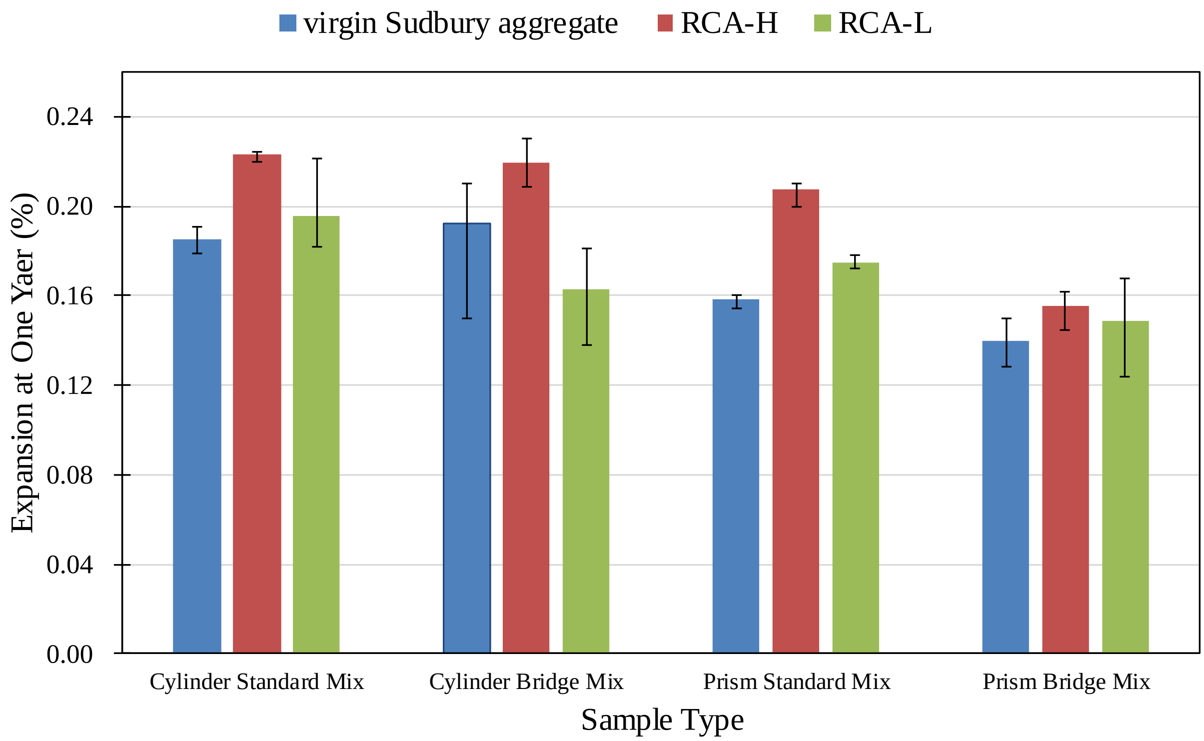


Fig. 6. Expansion of concrete prisms and cylinders with standard and bridge mixtures with the error bar representing min/max values of the three specimens

In general, the three aggregates did not show much difference in expansion within each sample type (cylinder or prisms) and mix type (standard or bridge), although the RCA-H showed slightly higher expansions. The expansion obtained in this paper suggests that the RCA deterioration level does not significantly affect the expansion of new concrete for the material tested here. This finding does not agree with other research work [4], where RCA from high deteriorated concrete showed less expansion when used in new concrete. The low expansion was attributed to the increased consumption of the reactive silica during the service life of the highly deteriorated concrete [4]. However, the RCAs used here and in [4] were not from the same source or of the same composition. The findings of this paper, on the other hand, are in agreement with the other research work [7]. The reason for the independence of the RCA reactivity on the level of deterioration of the source concrete could be that when processing RCA from the barriers or old elements, fresh faces of the original stone are being exposed, leading to similar expansion regardless of the original level of deterioration [2]. The slightly increased expansion of concrete with RCA-H could be due to further swelling of the existing and excessive ASR gel within the RCA, as demonstrated earlier in Figures 3 and 4. In an earlier study, concrete with RCA showed higher expansion than concrete with the same virgin aggregate for a siliceous limestone reactive aggregate from Ontario, Canada (Spratt) [2], although this was not the case in other work [4]. The reported high expansion was attributable partly to the alkali contribution from the residual mortar of RCA [2], which could be a contributing factor in this study. Measuring the amount of residual mortar in the RCA tested here could have been helpful. However, the level of alkalis contributed from each type of RCA was evaluated here and found similar as reported earlier. Knowing that RCA consists of the original stone and surrounded residual mortar, it is anticipated that the volume of the original reactive aggregate in concrete with RCA is less than that in concrete with virgin aggregate. Obtaining similar expansion of concrete with RCA and concrete with virgin aggregate suggests that the level or extent of reaction in the sample with RCA (less volume of reactive stone) is higher. In addition to alkali contribution from residual mortar, the expansion of existing gel - as stated earlier - could be a contributing factor to the increased expansion of concrete with RCA. Moreover, it has been reported [7] that crack propagation in the case of concrete with RCA requires less energy than forming new cracks in the case of concrete with natural aggregates. All samples exceeded the acceptable CPT expansion limit of 0.040% well before the CSA specified one year.

The expansion of the cylinders was higher than that of the prisms for each investigated mix, which agrees with earlier work [33]. The concrete prism expansion of the standard mix was higher than that of bridge mix for all samples, which is expected due to higher Portland cement or alkali content. The difference between the expansion of the standard and bridge mix using cylinders was not as large as the case with the prisms. The reason for this observation is not investigated in detail. However, it has been demonstrated that Sudbury shows a sharp increase in expansion within certain alkali levels, after which the effect of alkali is not as significant [23]. It is possible that the reduced leaching in the case of cylinders [33,35] maintained the alkali content in both mixes within the alkali range that produces similar expansion. On the contrary, the higher alkali leaching in prisms could have brought the levels of alkalis in the two samples or mixes to the range of alkali content within which different alkali levels produce significantly different expansion.

The effect of silane on lab-prepared and tested samples is shown in Figure 7, reflecting expansion reductions ranging between 0.005 to 0.06 percent points - which are 2.7% to 30% of the average expansion. In general, the application of silane to lab-prepared samples tested under lab conditions reduced the expansion but not enough to meet the 0.040% expansion limit at one year. The graph shows that the silane was slightly more effective in cylinders, likely due to the ease of silane application on a curved surface rather than the prisms with multiple edges.

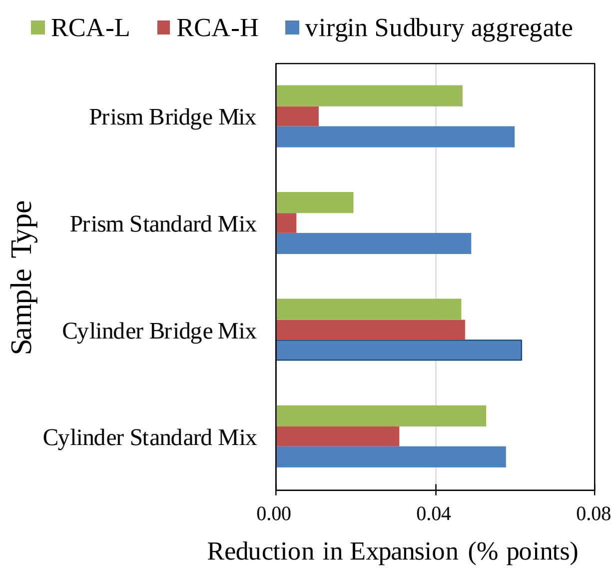


Fig. 7: Reduction in expansion due to the application of silane

A comparison of the expansions of extracted cores and those of concrete cylinders made with RCA and exposed to the same testing conditions (38°C and 100% RH) is shown in Fig. 8. As the figure shows, the rate of expansion was higher for the extracted cores at early ages, suggesting a "continuation of expansion" contrary to the case of cylinders with RCA where the rate of expansion was slow at earlier ages, indicating a start of the reaction. In the case of extracted cores, the expansion of undisturbed ASR gel could be the reason for the observed high rate of expansion at early ages. The expansion of gel could also be a contributing factor in the case of concrete with RCA, although the processing of RCA, which involves natural drying, could have delayed the onset of the gel swelling. Ultimately, concrete with RCA showed much higher expansion than extracted cores due to the added alkalis contributed by the PC in the new mix and perhaps exposing fresh faces of the reactive stones within the RCA.

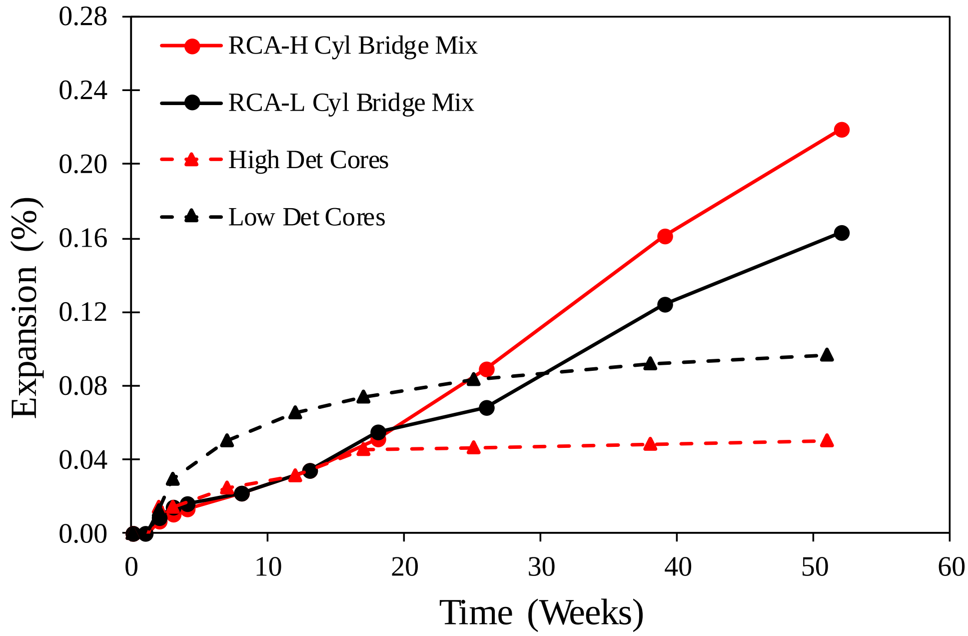


Fig. 8. Expansion of cores and cylinders of similar composition

3.4. Effects of SCM on Mitigating the Expansion

The expansions of concrete prisms without preventive measures at one year and with different levels and types of SCM at two years are shown in Figure 9 for Sudbury virgin aggregate and Sudbury-RCA (RCA produced from different panels without separation based on level of deterioration). The mixtures were prepared following the standard concrete prisms test [25] with total cementing materials of 420 kg/m^3. The graph shows similar levels of SCM to produce higher expansions in concrete with RCA. This finding is consistent for all samples. The results confirm the earlier findings that concrete with reactive RCA requires higher levels of SCM to mitigate expansion [2,20,22] compared to concrete with the same reactive stone in the RCA.

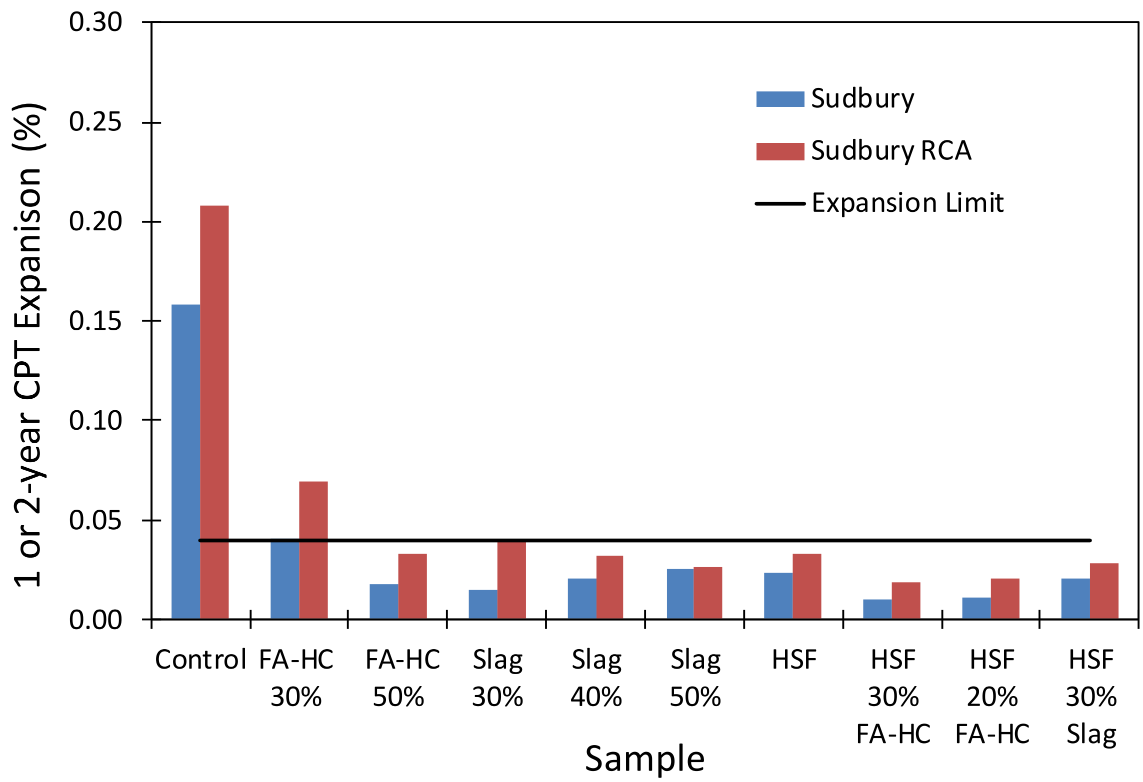


Fig. 9. Effect of SCM on reducing the expansions in concrete prisms containing Sudbury and Sudbury-RCA

3.5. Efficacy of Accelerated Test Methods to Evaluate Expansion and Preventive

3.5.1. Accelerated Mortar Bar Test

The accelerated mortar bar procedures modified to be suitable for RCA [22,26,27] as presented in subsection 2.2.5 were used to evaluate RCA with and without SCM. In addition, the standard test method [34] was applied to mortar bars containing virgin Sudbury with and without SCM. A relationship between the 14-day expansion of mortar bars and the one or two-year expansions of concrete prisms with and without SCM, respectively, is shown in Fig 10a. The graph shows the correlation and the expansion limits for both tests. There is a general agreement between the two tests, with the majority of samples passing both tests. There are no samples that passed the AMBT and failed the CPT showing that the test is a safe indicator of the reactivity and efficacy of preventive measures. Few samples failed the AMBT and passed the CPT, reflecting that AMBT might provide conservative results or false positives in some cases.

In Figure 10b., the data from the current study is combined with data from Johnson and Shehata [27] for another natural reactive aggregate, Spratt - a siliceous limestone, from Ontario, Canada, and reactive RCAs from different sources. The natural reactive aggregate Spratt was tested at different replacement levels of the total coarse aggregates in the mix to provide different levels of expansions. The results further demonstrate the possibility of using the AMBT to evaluate the reactivity and preventive measures of natural aggregate and RCA. There is a limited number of samples with Sudbury aggregates showing false positive; i.e, failing the AMBT and passing the

CPT. These results do not impose a safety risk on using the test, rather, they call for higher levels of preventive measures.

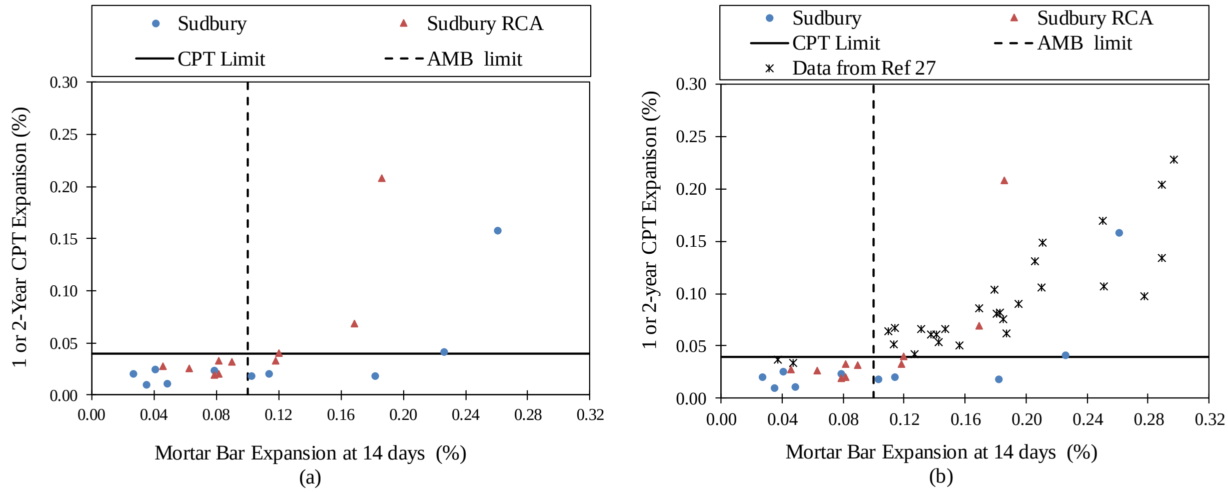


Fig. 10. (a) Expansions of CPT versus expansions of AMBT for (a) samples from the current study and (b) results from the current study plus those from Ref. 21.

3.5.2. Concrete Microbars

The reactivity of virgin Sudbury and RCA containing Sudbury aggregate was investigated using the concrete microbar test method [28], with a modified sample length, as described in subsection 2.2.5. The expansion was measured until 56 days to examine the test capacity to evaluate the reactivity of virgin Sudbury aggregate and Sudbury RCA. The RCA used for these specimens consisted of the mixed RCA (Sudbury-RCA). The test was done with two aggregate sizes: 4.75mm to 9.5mm and 9.5mm to 12.5mm. Although the standard method specifies using size 4.75mm to 9.5mm, the larger aggregate size was tested to determine which size yields higher expansion values or is more suitable for assessing the reactivity of RCA. As Shown in Fig. 11, the smaller size (4.75mm-9.5mm) showed higher expansion compared to the large size at 28 and 56 days, with the exception of RCA at the age of 28 days, where both sizes showed the same expansion. Also, mixtures with RCA showed higher expansion compared to mixtures with virgin aggregate, which is in agreement with the CPT results but not in agreement with earlier works [2,27]. In the work of Shehata et al. [2], virgin siliceous limestone aggregate (Spratt) showed slightly higher expansion than RCA containing the same aggregate when tested by the CMBT. In the work of Johnson and Shehata [27], the three tested virgin aggregates showed the same or slightly higher AMBT expansion than RCAs containing the same virgin aggregates. In any case, both virgin and RCA tested in the current study failed both criteria suggested by Johnson and Shehata [27] (an expansion limit of 0.04% at 28 days or 0.10% at 56 days), as shown in Figure 11. In other words, both limits were able to detect the reactivity of both virgin aggregate and RCA tested here. Based on the results from Fig. 11, the remaining CMBT program - which involves testing aggregates with SCM - was carried out using the small size, i.e., 9.5 mm to 4.75 mm.

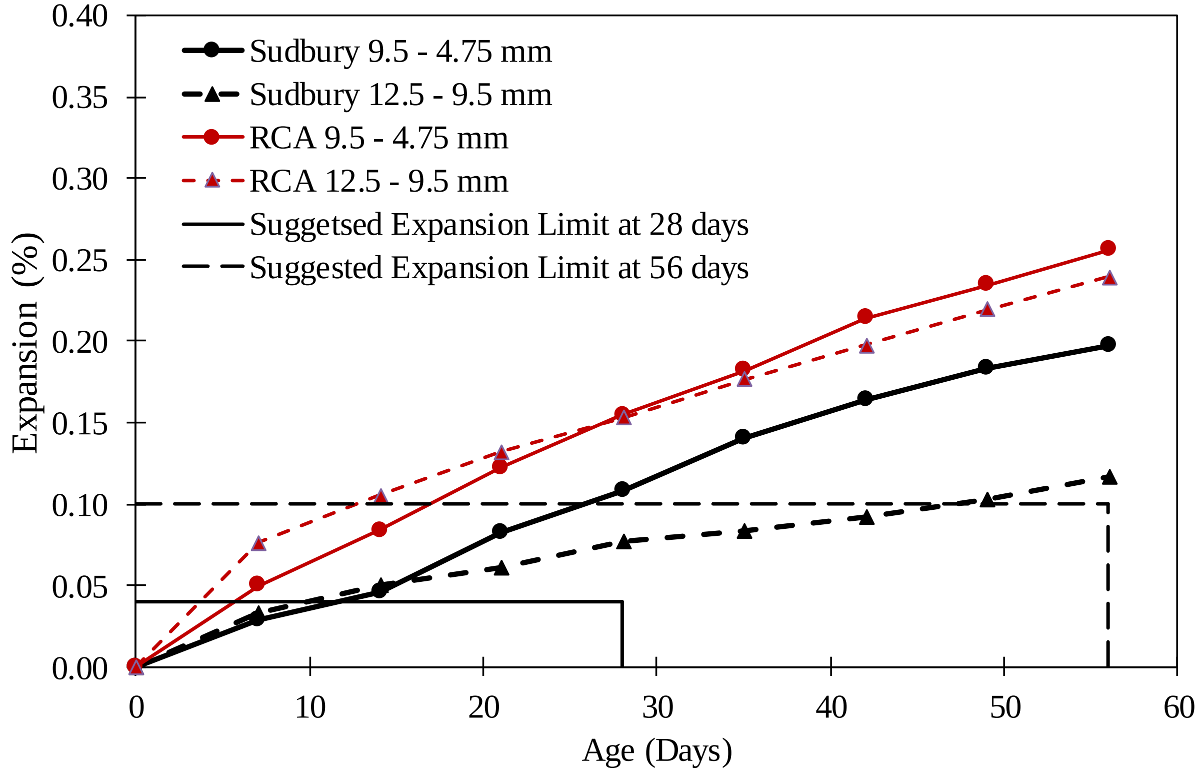


Fig. 11. Expansion of concrete microbars containing virgin Sudbury aggregate and Sudbury-RCA

The relationship between the CPT expansions - at two years for samples with SCM and one year for samples without - versus the expansions of microbars at 28 days or 56 days are shown in Fig 12a and 12b, respectively. Based on the graphs, the suggested expansion limits of 0.04% at 28 days or 0.10% at 56 days [27] provide a conservative estimation of the CPT expansion. In other words, there is no sample that passed the CMBT and failed the CPT. It can be seen in Fig. 11a and 11b that both limits can be relaxed or increased. This will be discussed after looking at the data from the current study combined with data from the work of Johnson and Shehata [27] for different types of RCA and a siliceous limestone reactive aggregate, Spratt.

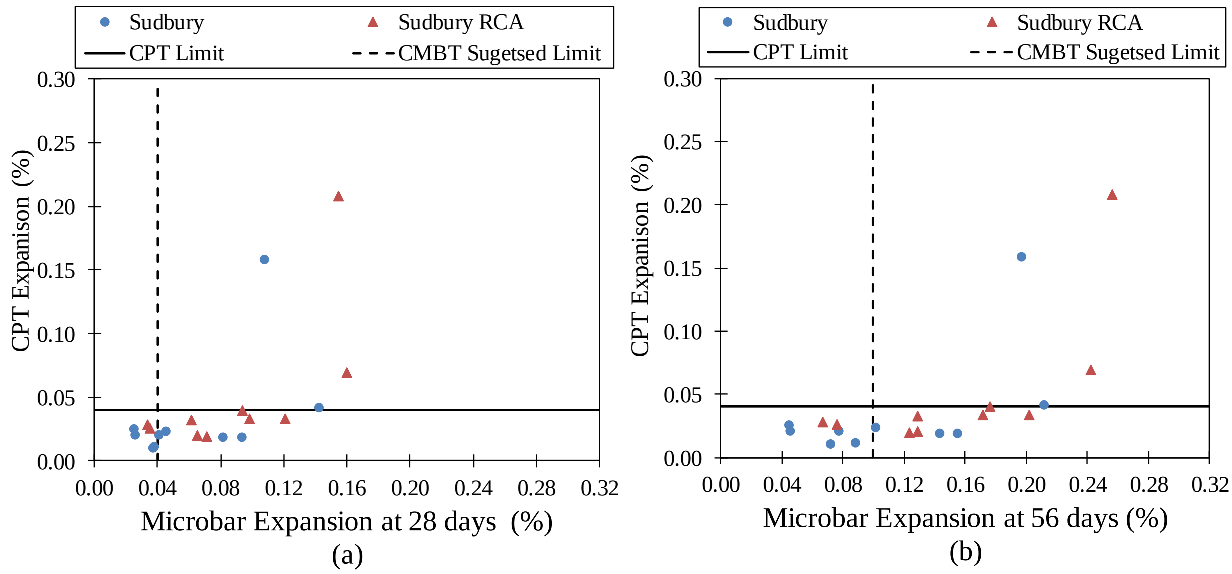


Fig. 12. Expansions of CPT at two years for samples with SCM and one year for samples without SCM versus the AMBT expansions at (a) 28 days and (b) 56 days.

The results of CPT Versus CMBT expansions for the samples tested in the current study combined with data from [27] are presented in Fig. 13a and 13b. The data from Ref [27] includes RCAs from different sources: natural siliceous limestone aggregate, Spratt, blended with a non-reactive coarse aggregate at replacement levels ranging from 0% (non-reactive) to 100 %, and Spratt-RCA with SCM.

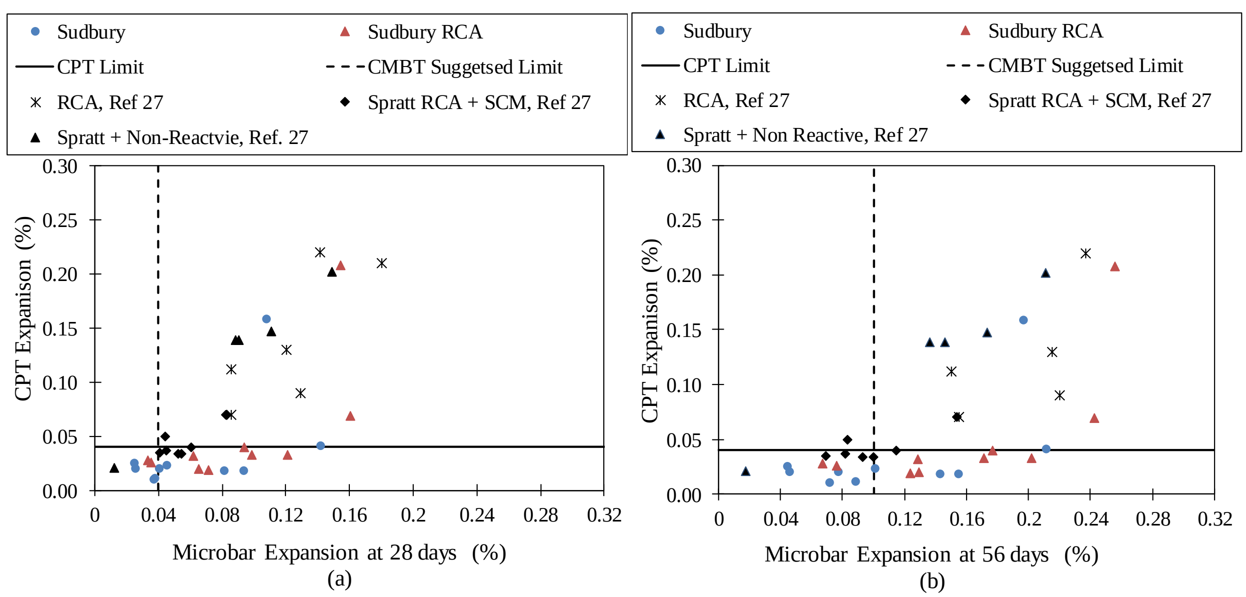


Fig. 13. Expansions of CPT at two years for samples with SCM and one year for samples without SCM versus the AMBT expansions at (a) 28 days and (b) 56 days. The graphs include data from the current studies and from Ref. [27].

As shown in Fig.13, the proposed expansion limits in [27] still provide a safe approach to predicting CPT expansion when data from this study are included. The only sample that passed the 56-day limit and failed the CPT - with a small margin - is a blend of 5% silica fume/45% slag used with RCA containing Spratt [27]. A number of samples failed the CMBT and passed the CPT or showed a false positive. These samples contained the reactive gravel, Sudbury, with some of the tested types and levels of SCM. This observation implies that higher levels of the same SCM or different types would be required to bring the expansion to the acceptable level. In other words, this finding does not prevent the use of the tested RCA; rather, it implies that different levels or types of preventive measures are needed. While the expansion limits can be relaxed to perhaps 0.06% and 0.12% at 28 days and 56 days, respectively, the authors believe that based on the available data, it is safer to keep the expansion limit as suggested. The reason is that samples that exceed the 0.06% and 0.12% expansions at 28 and 56 days in CMBT with a relatively small margin failed the CPT with a large margin. It should be noted that the RCAs tested in reference [27] and presented in Figure 13, included five different RCA containing different reactive stones, namely natural gravel, argillaceous limestone, siliceous sandstone, greywacke/argillite [27], and fine-grained Ordovician limestone [4,27]. These five types of RCA were tested without SCM. The sixth type of RCA, siliceous limestone, was tested with and without SCM. All six types of RCA failed both CPT and CMBT using the suggested expansion limits shown in Fig 13. In the early work of Grattan-Bellew et al. [30], the authors suggested expansion limits of 0.04% for assorted aggregates and 0.09% for siliceous limestone at 30 days. When testing the same siliceous limestone, Spratt aggregate, blended with non-reactive aggregates at different ratios, and Spratt-RCA with SCM in ref [27], the expansion limit of 0.09% at 28 days would give a false negative as shown in Fig. 13a [31]. Hence, the expansion limit suggested here provides a safe evaluation but can give false positives with some cementing blends.

4. DISCUSSIONS

The results presented here demonstrated that new concrete with ASR-affected RCA produced much higher expansions than cores extracted from the same elements from which the RCA was produced. Hence, the low expansion obtained in the cores tested in this study is due to their relatively low alkali content rather than the depletion of reactive silica during the structure service life. In fact, cores from the same barriers showed very high expansion when stored in an alkaline solution of 0.60 moles/litre [35]. The silica in the produced RCA was enough to trigger very high expansion when used in new concrete with additional Portland cement or alkalis. The alkalis in the original structure or cores could be consumed during the ASR reaction, leached out of the concrete elements during service life, or leached out of cores during testing in the lab above water.

The results presented here showed that the level of deterioration in existing elements due to ASR does not affect the expansion of new concrete containing recycled aggregates from such elements. This finding might not apply to all RCA; for example, Beauchemin et al. [4] reported an opposite trend due to less reactive silica in the structures with high deterioration. In the current study, the RCA from highly deteriorated elements produced slightly higher expansion than RCA from low deterioration elements. The slight increase in expansion could be due to the swelling of existing gel - which could be more abundant in the case of RCA from high deterioration elements. The use of sealers reduced the expansion but did not prevent it. Hence, its use to delay expansion in the existing structure could be a good strategy, especially at the early stages of the deterioration when the cracking is not extensive.

Although cylindrical samples were used here to compare the expansion of new concrete to cores, the results confirmed the earlier finding [33] that cylinders produce higher expansions than prisms. The reason was the reduced alkali leaching from cylinders during the testing period [33].

In terms of accelerated test methods, two methods were examined in this study for their ability to evaluate reactivity and efficacy of preventive measures. The results from these two tests were compared with the CPT expansion as it - the CPT - is considered the most reliable lab test for ASR [36]. Expansion data from exposure sites would have been more reliable and useful to compare to; however, such data is scarce, especially for concrete with RCA. The AMBT shows excellent efficacy for predicting the expansion of concrete prisms. However, careful sample preparation is essential as inadequate preparation can result in processed RCA with more residual mortar than reactive stone, leading to less expansion [27]. Hence, extra attention to sample preparation and correction for the absorption of the RCA is essential when using the AMBT [2,24,26,27].

Compared to the AMBT, the CMBT has the advantage of less processing of aggregate. Hence, the possibility of obtaining an unrepresented sample or sample with more residual mortar than that in the original coarse RCA is less than in the case of the AMBT. In addition, for some reactive sandstones, the accelerated mortar bars can underestimate the expansion as reported in [32] and demonstrated in [27]. The two factors mentioned above attract the attention of the CMBT as an accelerated test method.
Based on the collective data, the following limits and acceptance criteria are suggested:

(i) For expansion ≤ 0.04% at 28 days, the aggregate/cementing blend is safe for use in concrete,

(ii) For expansion ≥ 0.10 % at 28 days, the aggregate/cementing blend requires further testing by CPT or is not safe for use in concrete, and

(iii) For expansion > 0.04% and < 0.10% at 28 days, the test should continue until 56 days. If the expansion at 56 days is ≤ 0.10%, the aggregate/cementing blend is safe for use in concrete; otherwise, CPT is needed, or the aggregate/cementing blend is not suitable for concrete.

The above-suggested limit allows for safe aggregate/blends to be detected in 28 days and to extend the testing to 56 days only when needed. With the implementation of the 56 day-limit, the number of samples with pass/pass criterion increased from 8 samples - at 28 days - to 14 samples at 56 days. In other words, 6 samples in the expansion category of 0.04% to 0.10% at 28 days met the requirements of ≤ 0.10% at 56 days. While the expansion limits of 0.04% at 28 days or 0.10% at 56 days are somehow conservative, the limits can be relaxed with more data becoming available. It should be noted that the CMBT results presented here for aggregate/cementing blend combinations are for two types of aggregate: gravel and siliceous limestone. More aggregates sources with SCM or preventive measures need to be tested to ensure that the suggested expansion criteria apply to a wide range of aggregates/cementing blends.

5. CONCLUSIONS

Based on the material tested here, the following conclusions are made:

1. Concrete containing alkali-reactive RCA produced similar or higher expansion than concrete containing the original virgin aggregate.

2. The level of deterioration in the source concrete elements did not significantly affect the reactivity of the produced RCA. This finding suggests that the reaction occurs at the newly crushed faces of the aggregate.
3. Expansion of cores from low-deterioration elements was higher than that of the high deteriorated cores. This finding suggests that the excessive cracking in the high deteriorated cores allows the expansive gel to navigate within the cracks and show less expansion.
4. Concrete cylinders showed higher expansions than concrete prisms of the same mix.
5. Silane-based sealers reduced expansion due to ASR - in samples tested under lab conditions - but did not prevent it.
6. Reactive recycled concrete aggregate requires higher levels of SCM, compared to natural reactive aggregates, to reduce the CPT expansion to lower than 0.040% at two years
7. For the materials presented here, the accelerated mortar bar test modified to accommodate the intrinsic properties of RCA was effective in predicting the expansion of concrete prisms for RCAs and natural reactive aggregates, with and without SCM.
8. The concrete microbar test with the proposed limits suggested here can be used to provide an accelerated and safe prediction of the expansion of concrete prisms containing RCA or natural reactive aggregates with different cementing blends. However, more aggregate sources need to be tested.

6. ACKNOWLEDGEMENTS

This research is funded by a grant from the Ontario Ministry of Transportation (MTO) under the Highway Infrastructure Innovation Funding Program and an NSERC Discovery grant. The financial support of both organizations is highly appreciated. Opinions expressed in this paper are those of the author and may not necessarily reflect the views and policies of the Ministry of Transportation, Ontario. The authors would also like to thank Dr. Noura Sinno of Ryerson University for her help with the measurements of the concrete samples.

Credit authorship contribution statement

Matthew Piersanti: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Medhat H. Shehata**: Supervision, Conceptualization, Methodology, Project administration, Formal analysis, Funding acquisition.

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