EXPANSION OF CONCRETE CONTAINING REACTIVE RECLAIMED CONCRETE AGGREGATES OF DIFFERENT REACTIVITY AND COMPOSITION

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Abstract

Through earlier studies, Recycled Concrete Aggregate (RCA) produced from reclaimed concrete material containing Alkali-Silica Reactive aggregate of high reactivity was found to cause expansion when used in new concrete. The level of preventive measures required to reduce the expansion to an acceptable level was higher for concrete with RCA than it was for the original concrete produced with the same aggregate. This finding motivated the authors to investigate if this would be the case if RCA was produced from concrete containing moderately reactive aggregates of different composition. The results confirmed the earlier finding although the expansion was generally lower than the earlier case with concrete containing highly reactive virgin aggregate or RCA. The testing carried out here supported earlier findings according to which the Concrete Microbar test can be a promising tool to evaluate reactivity of RCA.

Keywords: reclaimed aggregate, alkali-silica reaction, supplementary cementing materials, concrete prism test, concrete microbar test

1 INTRODUCTION

When concrete structures are demolished, they produce a large amount of material which can contribute to environmental disposal issues we have today. Disposing construction wastes in landfills consumes land space and has negative economic and environmental impacts. It has been found out that demolished concrete can be recycled as aggregate used for new construction. As environmental awareness becomes a more pressing issue in the construction industry, it is important to determine what types of recycled concrete aggregate (RCA) is available and where it can be used. Specifically, this paper looks into the use of RCA produced from demolished concrete affected by alkali-silica reaction (ASR). In order to do so, it is important to know the type of RCA proposed for use, its reactivity, and its potential for causing future expansion/disruption. For example, a study was completed by Shehata et al. (2010) on highly reactive virgin siliceous limestone aggregate from the Spratt quarry in Ontario and reclaimed RCA containing the same aggregate [1]. The RCA was collected from 12-year old test blocks that were part of an exposure site. It was found that this RCA produced higher expansion than the original aggregate, and the levels of preventive measures required to mitigate the expansion was higher for the RCA. The present study investigates the reactivity of RCA produced from reclaimed concrete containing moderately reactive aggregate from gravel pits near Sudbury, Ontario. The findings of the current study adds to the knowledge in this area since the tested aggregate is of different origin and lower reactivity.

Alkali-silica reaction is a deterioration mechanism that causes expansion and cracking in concrete in the presence of the following three components – alkalis, reactive aggregate, and water. The reaction occurs with the presence of sodium (Na+) and potassium (K+) ions and their accompanying hydroxyl ions (OH-) [2]. The high pH level in concrete allows the hydroxyl ions to intrude on the reactive silica (SiO_2), causing it to disintegrate. Water is absorbed from nearby cement paste by the calcium-based gel, which causes swelling and expansion around or within the aggregate. This expansion causes an increase in pressure, which inevitably causes the concrete to crack [2]. A Scanning Electron Microscope image showing the formation of gel in reactive Spratt aggregate and illustrating the resulting cracking and disruption is shown in Figure 1. This image was obtained through the earlier study on RCA containing siliceous limestone Spratt aggregate [1].

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When reactive aggregates are used in concrete, mitigation methods, such as the use of supplementary cementing materials (SCM) or chemical admixtures such as lithium salts, are necessary. Sealers can also be used on existing structures to mitigate or reduce the rate of expansion. The use of SCM is the most common and preferred method, specifically fly ash, slag, and silica fume. It was found that silica fume may reduce expansion but only for a short period of time, thus longer testing times are required [3]. The level of alkalis in the SCM is also very important because additional alkalis will stimulate expansion. Thus, SCM with low alkalis is preferred in mitigating expansion due to ASR [4]. Tests were performed on a silane-based sealer on road barriers and found that, over 10 years, sealed barriers produced less surface cracks and expansion [5]. The internal relative humidity of the barrier with silane was found to be lower [5] and perhaps this is the reason for the measured lower expansion. The same study also found that the sealer was able to stop expansion for at least 6 years in severely affected barriers and likely over 10 years in moderately deteriorated barriers.

RCA produced from concrete affected by ASR was found to cause severe damage if used as aggregate in new concrete. Shehata et al. (2010) compared expansion of Spratt and Spratt RCA aggregates in concrete prisms, in which it was found that expansion results do not vary significantly between the two [1]. Shehata et al. (2012) went further looking into mitigation methods such as using SCM and mixing reactive coarse RCA with non-reactive coarse aggregate in an effort to reduce expansion [6]. The results showed that some ternary SCM blends were effective enough to reduce the 2-year expansion of 100% RCA aggregate below the 0.040% limit specified by Canadian Standards (CSA A23.2-27A) for concrete with natural aggregates. The study also found that using 70% reactive RCA and 30% non-reactive aggregate significantly reduced the expansion and was able to reduce it below 0.040% over 2 years when used with SCM. Although significant SCM was necessary to reduce Spratt RCA below the 0.040% limit at 2 years, including ternary blends, this may not be the case for other types of RCA, including the type used in this study produced from concrete containing Sudbury aggregate. Besides the fact that Sudbury RCA has a lower rate of reaction, Shehata and Thomas (2010) found that the Spratt aggregate requires less alkali content to cause excessive expansion [7]. For example, concrete prisms containing Spratt aggregate with 0.80% Na_2O_e-cement expands beyond the acceptable limit, while concrete prisms with Sudbury aggregate do not. Furthermore, when Spratt prisms contain Portland cements of 0.94% or higher Na_2O_e, the expansion increases immensely (up to 0.24% expansion at 1.2% Na_2O_e), while Sudbury prisms remain at 0.17% expansion. Thus, using SCM will aid in lowering the alkali content of a concrete and is thought to potentially have a greater effect on reducing expansion when using the Sudbury aggregate than with the Spratt aggregate. On the other hand, Sudbury aggregate contains alkalis and the released alkalis overtime, might reduce the efficacy of SCM. These factors motivated the authors to carry out this research.

The main objectives of the research presented in this paper are: (1) to investigate reactivity of RCA reclaimed from ASR-affected structures containing moderately reactive aggregate, (2) to determine if there is a difference in the level of expansion that occurs between a moderately reactive aggregate and reclaimed RCA with the same aggregate , and (3) to determine the types and levels of SCM that are required to mitigate expansion in new concrete that contains RCA with a moderately reactive aggregate.

2 MATERIALS AND EXPERIMENTAL DETAILS

2.1 Materials

Aggregates and cementing materials

The two types of coarse aggregate tested in this study were the Sudbury aggregate and reclaimed RCA containing the Sudbury aggregate. The Sudbury aggregate is produced from gravel pits near Sudbury Ontario Canada. They contain argillite, greywacke, and quartz-wacke rock types and are known to be alkali-reactive. The RCA investigated in this study was produced from the barrier walls of a more than 20 year old concrete bridge that were cast with Sudbury coarse aggregate, . These road barriers suffered varying degrees of deterioration due to ASR and freezing and thawing. The condition of some of the road barriers may be classified as highly deteriorated as shown in Figure 2.

The dry Bulk Relative Density (BRD) and water Absorption were tested in the lab for both Sudbury gravel and Sudbury RCA. The BRD for Sudbury gravel was found to be 2674 kg/m^3 with Absorption of 0.539% while Sudbury RCA has a BRD of 2359 kg/m^3 and Absorption of 3.873%. The types of cementing materials used in this study include General Use (GU) Portland cement, HSF blended cement (containing 8% silica fume), high calcium fly ash (FA-HC), low alkali and low calcium fly ash (FA LA-LC), high alkali and low calcium fly ash (FA HA-LC), and slag. These are similar to the SCM used in an earlier study by Shehata et al., 2010, which enabled comparing the level of preventive measures required to counteract the expansion in two types of RCA: highly reactive and moderately reactive [1]. The oxide compositions of the various cementing materials used are shown in Table 1. When comparing these oxide compositions with those used by Shehata et al., 2010 [1], listed in Table 2, it can be seen that the compositions of some of the SCM are similar. That is, FA-HC is similar to CH-LA, FA LA-LC is similar to F-LA, and Slag is similar to SG. In addition, when taking 92% of the composition of HAPC and 8% of the composition of SF (from Table 2), the composition is similar to that of the HSF cement, which contains 8% silica fume, from Table 1. Therefore, samples containing 8% SF from the study completed by Shehata et al. (2010) [1] for Spratt and Spratt RCA will be compared to Sudbury and Sudbury RCA samples cast with HSF blended cement.

2.2 Sample Preparation

Different samples were prepared including concrete prisms and concrete microbars containing both Sudbury aggregate and Sudbury RCA as shown in Tables 3 and 4. The samples used in this investigation are: (1) concrete prisms containing Sudbury aggregate and Sudbury RCA with varying types and levels of SCM, and (2) microbars containing virgin Sudbury aggregate and Sudbury RCA with varying types and levels of SCM. The samples were tested following CSA A23.2-14A [8]. The coarse aggregate gradation for both virgin aggregate and RCA prisms follow the guidelines of the concrete prism test and contain non-reactive sand as fine aggregate. The samples cast with RCA were used as a 100% replacement for coarse aggregate. The alkalinity of the cement was raised to 1.25% for concrete prisms while concrete microbars were raised to 1.5% Na_2O_e, as per RILEM standards [9].

2.3 Experimental Procedures

Concrete prism test

The concrete prism test (CPT) was followed as per CSA A23.2-14A [8] to determine expansion due to ASR, which requires a 60:40 ratio of coarse-to-fine aggregate. A water-cement ratio (w/c) of 0.45 was used. All procedures outlined in the standard were followed including mixing, rodding, and curing of the samples. The RCA aggregate was not washed in order to prevent leaching of alkalis from any possible residual mortar. After 24 hours of curing, buckets were lined with cloth and the prisms were placed inside, raised above water. The buckets were placed in a room maintained at 38 °C and readings have been taken as per CSA A23.2-14A [8].

Concrete microbar test

The concrete microbar test was also used as per RILEM [9] to compare expansion in Sudbury aggregate and Sudbury RCA. Concrete microbars were cast using the standard aggregate size (4.75 mm – 9.5 mm) as well as 9.5 mm to 12.5 mm for both Sudbury gravel and Sudbury RCA. As per the standard, they were cast at a w/c of 0.33 and a 1:1 cement-aggregate ratio. In this testing, the w/c was corrected for absorption of the aggregate. These bars were cast as per the standard of 1.5% Na_2O_e. To do so, sodium hydroxide (NaOH) was added to the water to raise alkalinity of the Portland cement. After curing for 24 hours, the bars were placed in water at 80 °C for 24 hours before being placed in 1 N NaOH solution at 80°C for 56 days. Readings were taken as per RILEM until day-28 and once a week until day-56 [9].

3 RESULTS

3.1 Comparing concrete prisms containing Sudbury aggregate and Sudbury RCA

As per the CSA standard for testing ASR using the concrete prism test [8], concrete prisms containing SCM are to be monitored and measured for 2 years to determine if the mixture can be considered safe for use. Concrete prisms not containing any form of SCM, referred to here as a control mix, only require 1 year of testing. The expansion limit in both cases is 0.040%. Lab data has been collected so far for 1 year and 6 months to compare results of concrete prisms containing Sudbury aggregate and Sudbury RCA. Figure 3 shows the difference in expansion of the control prisms and prisms cast with varying levels and types of SCM. The figure clearly shows that the samples cast with Sudbury aggregate expand less than the samples cast with the same mix design containing Sudbury RCA. This is likely due to the additional alkalis present in Sudbury RCA derived from the residual cement paste. Swelling of existing gel in the RCA could also be a contributing factor. The expansion shown in Figure 3 clearly shows that the expansion of both control mixes greatly exceed the 1-year limit, whereas the mixes containing SCM are currently below the 2-year limit. When comparing the expansion of the virgin aggregate and the RCA containing SCM, it is clear that the use of SCM is effective in mitigating expansion in both cases. However, it seems that samples with RCA require a higher dosage of SCM to mitigate the expansion. Similar findings were found in the earlier study of Shehata et al., 2010 for highly reactive siliceous limestone [1].

3.2 Comparing microbars containing virgin Sudbury aggregate and Sudbury RCA

In addition to concrete prisms, microbars were also cast and tested using the concrete microbar test (CMBT) as per RILEM [9]. The RILEM test is intended to evaluate alkali-carbonate reactivity of aggregates, however, the authors believe it is a promising tool to evaluate alkali-silica reactivity as well. The work carried out here is a step towards evaluating the efficacy of this test to evaluate reactivity of primary aggregate and RCA and adding to the database of information pertaining to this test. Measurements were taken up to 56 days in order to determine the difference in reactivity between samples containing Sudbury aggregate and Sudbury RCA. Samples were cast with varying levels and types of SCM to determine the effects of SCM on the microbar samples, similar to that of the concrete prisms. A 28-day expansion limit of 0.040% has been suggested for this type of aggregate [10, 11] and was used here to evaluate the results.

Figure 4a shows the data collected of the Sudbury aggregate and Sudbury RCA control mixes containing two aggregate size ranges (4.75 mm – 9.5 mm and 9.5 mm – 12.5 mm). Figure 4b shows the data collected for the same two aggregate types containing varying levels and types of SCM for aggregates between 4.75 mm – 9.5 mm, as per the standard. Figure 4a shows that for both aggregate sizes, the Sudbury RCA expands at a higher rate than the Sudbury aggregate, similar to the results obtained using the concrete prism test. In addition, the expansion of the microbars cast with the control mixes greatly exceed the 0.040% limit at 28 days. For the Sudbury aggregate, the mixes containing the smaller aggregate size (4.76 mm – 9.5 mm) expand at a higher rate than the mixes containing the larger aggregate size (9.5 mm – 12.5 mm). For Sudbury RCA, the smaller aggregate showed higher expansion, but the difference was not that significant.

Looking at Figure 4b, it is clear that the mixes cast with Sudbury RCA and SCM expand at a higher rate than the mixes cast with Sudbury aggregate. Considering the 0.04% as the expansion limit, all the mixes containing SCM shown in Figure 4b would actually be considered ineffective. The test allowed, however, to differentiate between the different SCM blends. Comparing the results obtained for CMBT with those from CPT in Figure 3, especially for samples with Sudbury aggregate, one can argue that the CMBT overestimate the expansion of blends with SCM. However, this is a very limited set of data and more testing is needed to evaluate the efficiency of microbars to evaluate SCM.

3.3 Comparing results of siliceous limestone (Spratt) and siliceous metasediment (Sudbury) aggregates

The results obtained in this research were compared to the findings of Shehata et al. (2010) obtained using siliceous limestone aggregate (Spratt) and RCA containing Spratt aggregate [1]. These findings showed that much like Sudbury RCA tested here, Spratt RCA expanded at a higher rate than the Spratt aggregate, though the difference in expansion appears to be less in the Spratt aggregate. Figure 5a and 5b show comparisons between the expansion of the control mixes of the Spratt aggregates and the Spratt RCA. In Figure 5a, it is clear that the two sets of Spratt RCA tests (labelled Coarse RCA-1 and Coarse RCA-2), which showed expansion of 0.24% at 2 years, expand at a slightly higher rate than that of the Spratt aggregate, which showed an expansion of 0.22%. The difference in expansion was very low compared to the difference in expansion found between the Sudbury and Sudbury RCA. Unlike the Spratt aggregates, the Sudbury aggregates seem to continue to increase in expansion at a high rate after the first year. At the current 1.5 years, the Sudbury aggregate has expanded 0.20% while the Sudbury RCA has expanded 0.27%, resulting in a much larger difference in expansion than the Spratt aggregates.

With the addition of SCM, the expansion of both Spratt and Sudbury aggregates can be reduced to acceptable levels. Figure 6a, taken from Shehata et al. (2010), shows that with the addition of 50% high-calcium, low-alkali fly ash, CH-LA, the level of expansion for Spratt RCA can be reduced to about 0.12% at 2 years, while expansion of Spratt aggregate can be reduced to about 0.03% with the addition of 60% CH-LA [1]. Figure 6a also aligns with the findings presented in section 3.1, in which a higher dosage of SCM is required to reduce the expansion of the RCA. In Figure 6b, Sudbury and Sudbury RCA are shown with 30% and 50% FA-HC replacements. The 1.5 year data shows that the current expansion with 50% replacement is below the 0.040% limit, though the RCA may prove to expand more than 0.040% after 2 years. Additionally, the same trend follows between the Spratt and Sudbury aggregates, in that the RCA expands at a higher rate than the natural aggregates, and requires higher levels of SCM to mitigate the expansion.

Along with high calcium fly ash, data was obtained for samples cast with binary blends of silica fume or slag, shown in Figures 7a and 7b. In Figure 7a, the Spratt aggregates are shown with varying levels of silica fume and slag. With the use of silica fume, 10% was enough to mitigate expansion in concrete prisms with Spratt but was not enough for prisms with Spratt RCA. In Figure 7b, however, 8% of silica fume showed expansion lower than the 0.040% 2-year expansion limit after 78 weeks. It is unlikely that these samples will exceed the limit after 2-years (testing in progress). The concrete prisms with RCA produced higher expansion than prisms with natural aggregate for both Spratt and Sudbury materials. For slag, 50% was enough to mitigate expansion in prisms with Spratt but not with prisms containing Spratt RCA, as shown in Figure 7a. Expansion of prisms with Sudbury and Sudbury RCA are likely to be mitigated at slag dosage of 50%, as shown in Figure 7b. Thus, as shown by the data in Figures 5-7, it can be confirmed that the level of SCM required to reduce expansion for Sudbury aggregates is less than that of the Spratt aggregates. In addition, it can be confirmed that higher levels of SCM is required to reduce expansion of RCA.

4 DISCUSSION

The results presented here confirmed the earlier findings that RCA produced from ASR-affected concrete can lead to disruption and expansion if used in new concrete without preventive measures. While the aggregate used here is of different origin than that of the aggregate used in the earlier work by Shehata et al., 2010 [1], the same conclusions can be made. The difference between reactivity of the two aggregates was clear from the level of preventive measures required in each case. While the expansion values of concrete with RCAs were almost the same, and those for the natural aggregates were close, the level of required preventive measures were different. For the siliceous Spratt limestone, the levels of SCM were higher. This can be explained by the different reactivity of the two aggregates. In a study by Shehata and Thomas 2010, the levels of alkali content required to initiate expansion in prisms with Sudbury aggregate was higher than that required for Spratt [7]. Hence, same levels of SCM might reduce the pore solution alkalinity to the same level; however, that level could have been low enough to stop excessive expansion in concrete with Sudbury but not enough to suppress the expansion in concrete with Spratt.

Despite its main purpose, which is evaluating alkali-carbonate reactivity, the Concrete Microbar Test showed promising results in evaluating alkali-silica reactivity. Although the results presented here are limited, it shows the test to be a promising tool for this purpose. The authors are carrying out more testing to evaluate the efficiency of this test and its applicability to different aggregates. The advantage of this test lies in its shorter testing period compared to that of the concrete prism test. In addition, the test enables testing coarse aggregate without crushing to fine-aggregate size as required for the accelerated mortar bar test. The results presented here show this test to be effective in evaluating reactivity of RCA when the proposed limit of 0.040% at 28 days as suggested by Grattan-bellow et al., 2003 and 2004 is adopted [10,11]. Similar findings was reported by Shehata et al., 2010 [1] using siliceous limestone aggregate although the suggested expansion limit for this type of aggregate was 0.09% at 28 days as suggested by Grattan-bellow et al., 2003 and 2004 [10,11]. The results in Figure 7 show that the microbars could be used to evaluate efficiency of SCM, although the limited results presented here appear to overestimate the expansion, using an expansion limit of 0.040% at 28 days and referring to the results obtained from concrete prism test using the same combination of SCM.

In terms of applicability of the results obtained here, it is important to evaluate reactivity of RCA from demolished old structures. It should be emphasized that the RCA used here is sourced from 100% ASR-deteriorated old concrete. If the RCA is from mixed sources, it is likely that the percentage of reactive particles will be lower and the level of preventive measure will be lower as well. Moreover, blending reactive RCA with non-reactive natural aggregate is also a feasible option, not only in reducing the ASR and the levels of SCM, but also in optimizing other concrete properties including slump retention, shrinkage, strength, and durability.

5 CONCLUSIONS

1. Reclaimed concrete aggregate containing reactive siliceous gravel was found to cause a higher expansion than the original aggregate when used in concrete. This was also the case for a siliceous quarried limestone aggregate investigated in an earlier study.
2. The level of preventive measures required to mitigate expansion in concrete with RCA was generally higher that the levels required to mitigate expansion in concrete with the original aggregate. This was applicable to both the siliceous gravel and the siliceous quarried limestone aggregates.
3. Despite the limited tests carried out here, the Concrete Microbar test revealed promising results in evaluating reactivity of RCA.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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TABLE 1: Oxide composition of cementing materials.

Oxide	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	Total Alkalis (%)
GU Portland Cement	62.77	19.33	5.25	2.42	2.35	4.03	0.99
HSF Cement	55.97	26.15	5.03	2.18	2.22	4.02	0.96
FA-HC	26.41	34.01	18.35	6.32	6.09	1.39	2.11
FA LA-LC	3.67	47.36	23.86	17.4	1.0	1.08	1.86
FA HA-LC	7.24	60.67	17.09	4.92	2.46	0.61	3.68
Slag	39.9	36.9	7.82	0.68	11.2	0.45	1.10

TABLE 2: Oxide composition of cementing materials after Shehata et al. (2010).

Oxide	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	Total Alkalis (%)
HAPC[1]	62.8	19.6	5.35	2.29	2.43	4.10	0.96
SF[2]	0.27	96.2	0.35	0.10	0.91	0.25	0.55
SG[3]	43.2	34.4	7.4	0.94	9.30	0.83	0.95
F-LA[4]	4.43	55.7	27.4	5.59	1.56	0.26	1.95
CH-LA[5]	28.7	33.3	18.2	6.45	5.32	2.59	2.16

[1]HAPC: High-Alkali GU Portland Cement
[2]SF: Silica Fume
[3]SG: Slag
[4]F-LA: Fly Ash Type F (CaO < 8 wt.%) with low alkali content
[5]Fly Ash Type CH (CaO> 20 wt.%) with low alkali content

TABLE 3: Mix proportions for concrete prisms.

Sample ID[a]	Portland Cement (kg)	SCM		Coarse Aggregate (kg)	Fine Aggregate (kg)	Effective w/cm[b]
		Type	Mass (kg)			
Control	420	--	--	1050	700	0.45
30% FA-HC	294	FA-HC	126	1050	692	0.45
50% FA-HC	210	FA-HC	210	1050	686	0.45
30% Slag	294	Slag	126	1050	696	0.45
40% Slag	252	Slag	168	1050	695	0.45
50% Slag	210	Slag	210	1050	693	0.45
HSF Cement	386.4	Silica Fume	33.6	1050	696	0.45

[a] Each Sample ID was cast for 100% virgin Sudbury aggregate and 100% Sudbury RCA
[b] Effective w/cm values exclude the correction due to absorption of aggregates
[*] All mixes had alkali content raised to 1.25%

TABLE 4: Mix proportions for concrete microbars.

Sample ID[a]	Portland Cement (g)	SCM		Coarse Aggregate (g)	Water content (g)
		Type	Mass (g)		
Control[b]	1800	--	--	1800	580
50% FA-HC	900	FA-HC	900	1800	580
30% Slag	1260	Slag	540	1800	580
HSF Cement	1656	Silica Fume	144	1800	580

[a] Each Sample ID was cast for 100% virgin Sudbury aggregate and 100% Sudbury RCA
[b] The control mixes were cast for two different aggregate sizes (4.75 mm – 9.5 mm and 9.5 mm- 12.5 mm). All other mixes were cast with aggregates sized 4.75 mm – 9.5 mm as per the standard
[*] All mixes had alkali content raised to 1.5%

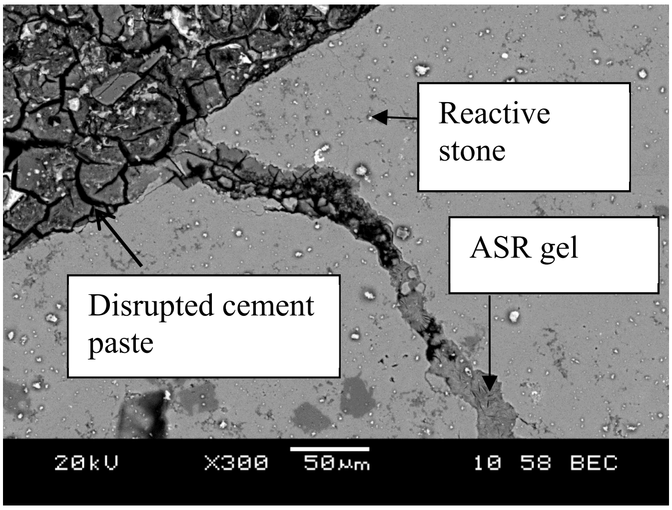

FIGURE 1: Scanning Electron Microscopy image showing the formation of gel in reactive aggregate.


FIGURE 2: Cracking of road barrier due to ASR and freeze-thaw deterioration.

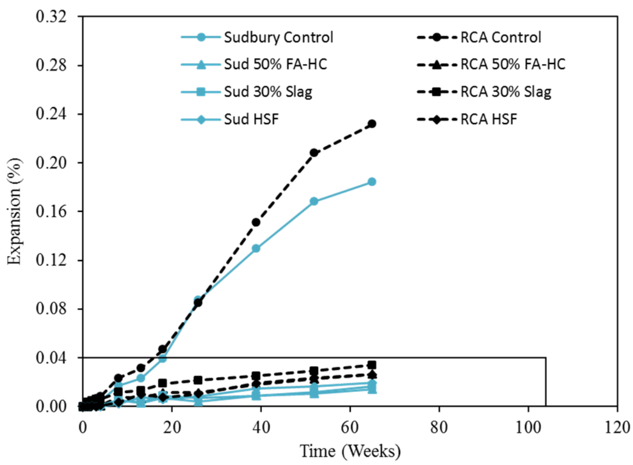

FIGURE 3: Expansion of concrete prisms containing virgin Sudbury aggregate and Sudbury RCA.

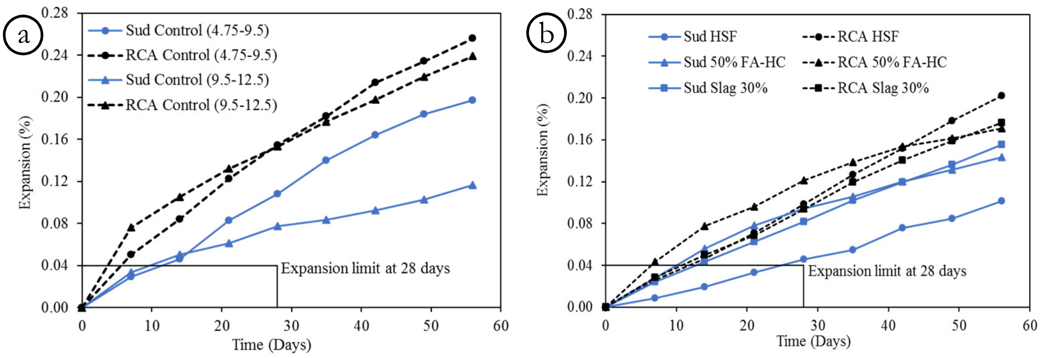

FIGURE 4: Expansion of concrete microbars containing Sudbury aggregate and Sudbury RCA.

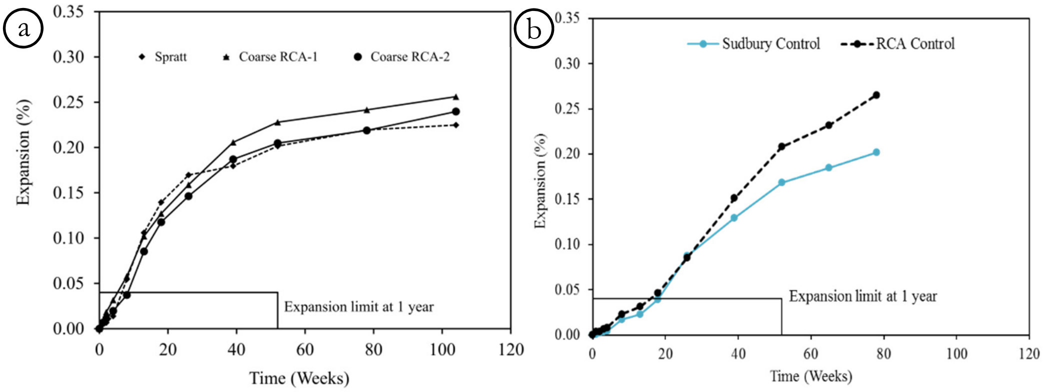

FIGURE 5: Control mix expansion results of Spratt aggregates (after Shehata et al., 2010) and Sudbury aggregates.

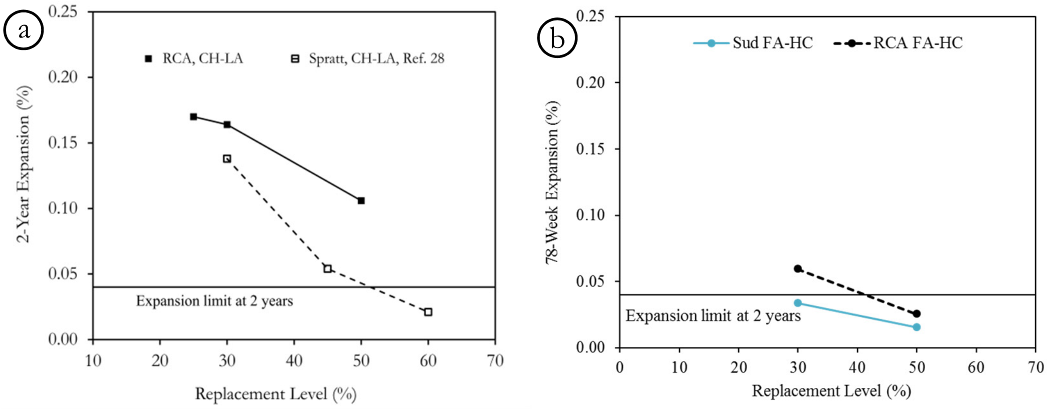

FIGURE 6:: Expansion results of Spratt aggregates (after Shehata et al., 2010) and Sudbury aggregates containing high calcium fly ash.

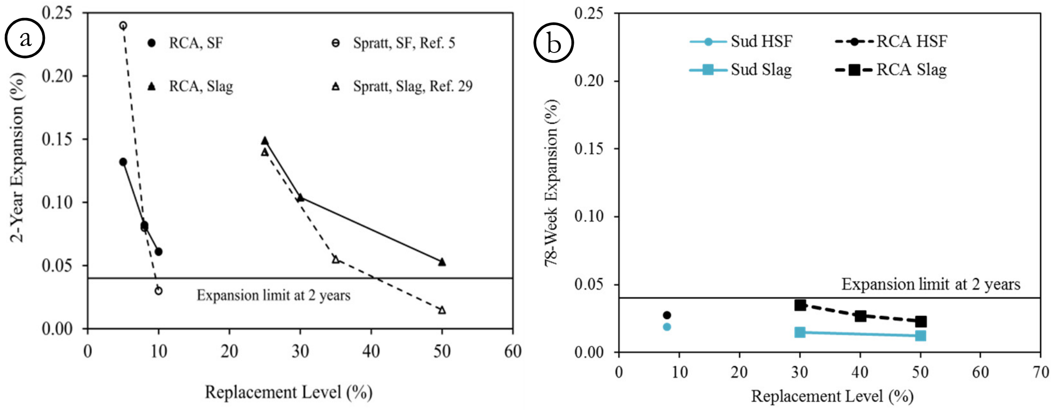

FIGURE 7: Expansion results of Spratt aggregates (after Shehata et al., 2010) and Sudbury aggregates containing silica fume and slag.