EXPANSION OF CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATE SUFFERING DIFFERENT LEVELS OF ALKALI-SILICA REACTION

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Abstract: The research presented in this paper compares expansion of concrete samples containing recycled concrete aggregate (RCA) suffering from alkali-silica reaction (ASR) to concrete with virgin aggregate of the same mineralogy. In the lab, expansion tests for ASR were carried out on samples that were cast with the same natural coarse aggregate along with recycled concrete collected from both high and low deteriorated road barriers. These samples were cast with two different cement contents and include concrete prisms and cylinders. The cylinders allow for investigating the effect of sample geometry on expansion and gave slightly higher expansion results. Expansion results up to the 26 weeks measured showed that RCA produced from high and low deteriorated panels produced similar expansion to each other but significantly higher than virgin aggregate. A silane-based sealant was found to mitigate expansion of the concrete. In addition, field measurements of expansion of concrete road barriers classified into two categories, high and low deteriorated, were taken and found to be significantly less than lab specimens.

1 INTRODUCTION

In Canada, the environmental conditions aid in the deterioration of concrete. When concrete continues to deteriorate and reaches the end of its service life, it is demolished and placed in landfills. In an effort to reduce the amount of waste produced by deteriorated concrete structures, many structures are being crushed into recycled concrete aggregate (RCA) and tested to determine its usability as an aggregate in new structures. The original aggregate used in the structure has a major impact on its usability as different precautions may need to be taken depending on its susceptibility. For instance, a structure containing aggregate that has suffered alkali-silica reaction (ASR) will continue to expand due to ASR in its new structure. Because of this, it is important to determine what level of deterioration has already occurred in the aggregate, whether the level of deterioration will have an effect on the new structure, and what precautions needs to be taken in order to mitigate the damages in the new structure.

Alkali-silica reaction is a deterioration mechanism that causes expansion and cracking in concrete with the presence of the following three elements – alkalis, reactive siliceous aggregate, and water. The reaction occurs with the presence of sodium (Na^+) and potassium (K^+) ions and their accompanying hydroxyl ions (OH^-) (Federal Highway Administration, 2012). The high pH level allows the hydroxyl ions to intrude on the reactive silica (SiO_2), causing it to disintegrate (Federal Highway Administration, 2012). Water is absorbed from nearby cement paste by the calcium-based gel, which causes swelling and expands around or within the aggregate. This expansion causes an increase in pressure, which inevitably causes the concrete to crack (Federal Highway Administration, 2012).

When reactive aggregates are used in concrete, mitigation methods are necessary, such as the use of supplementary cementing materials (SCM) or sealers. 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 for a short period of time, thus longer testing times are required, such as 2 years for the concrete prism test with SCM (Duchesne and Berube 1994). 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

(Shayan et al. 1996). Tests were performed on a silane-based sealer on road barriers and found that, over 10 years, sealed barriers produced less surface cracks (Berube et al. 2002). 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.

Recycled concrete aggregate (RCA) produced from concrete suffering 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 found that expansion results do not vary significantly between the two. Shehata et al. (2011) 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. The results showed that some ternary SCM blends were effective enough to reduce the 2-year expansion of 100% RCA aggregate below 0.04%. 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 0.04% over 2 years when used with SCM. Although significant SCM was necessary to reduce Spratt-RCA below the 0.04% limit at 2 years, including ternary blends, this may not be the case for other types of RCA, including the type used here produced from concrete containing Sudbury aggregate. Besides the fact that Sudbury RCA has a lower rate of reaction, Shehata and Thomas (2010) found that Spratt requires a far less alkali content to cause severe expansion. For example, concrete prisms containing Spratt aggregate with 0.8% Na_2O_e cement expands beyond the acceptable limit, while concrete prisms with Sudbury aggregate does not. Furthermore, when Spratt contains 0.94% or more Na_2O_e cement, the expansion increases immensely (up to over 0.5% expansion at 1.2% Na_2O_e), while Sudbury remains relatively stable (under 0.2% expansion at 1.25% Na_2O_e). Thus, using SCM will aid in lowering the alkali content of the concrete and is thought to potentially have a greater effect on reducing expansion on Sudbury than it did with Spratt.

Testing completed by the U.S. Department of Transportation in 2010 on the difference in expansion between cylinders and prisms. It concluded that rate of expansion in cylinders of both 150 mm and 200 mm diameter were larger than that of concrete prisms of the same aggregate. The study suggests that cylinders of 150 mm in diameter or larger reduce alkali leaching (U.S. Department of Transportation 2010).

2 MATERIALS AND EXPERIMENTAL DETAILS

2.1 Materials

2.1.1 Aggregates and Cementing Materials

The RCA used here was obtained from road barriers of a bridge in Sudbury, Ontario. The road barriers are over 20 years old and cast with Sudbury coarse aggregate, which is gravel containing argillite, greywacke, and quartz-wacke. These road barriers suffered varying degrees of deterioration due to ASR and freezing and thawing and were separated into two groups, classified as high deteriorated and low deteriorated barriers, shown in Figures 1 and 2.

Figure 1: High Deteriorated Barrier

Figure 2: Low Deteriorated Barrier

Measuring inserts (studs) were placed into both high and low deteriorated barriers to test for expansion in the field. RCA was reclaimed from both low and high deteriorated panels for lab testing. The Dry Bulk Relative Density (BRD) and absorption were tested in the lab for both Sudbury and Sudbury RCA aggregate. The BRD for Virgin Sudbury aggregate was found to be 2674 kg/m^3 with an absorption of 0.539% while Sudbury RCA has a BRD of 2359 kg/m^3 and absorption of 3.873%. The oxide composition of the cement used, General Use (GU) Portland cement, is shown in Table 1.

Table 1: Oxide composition of the Portland cement used

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	TiO_2	P_2O_5
GU Portland Cement (%)	62.61	19.33	5.25	2.42	2.35	3.99	0.80	< 0.01	0.28	0.13

2.1.2 Tested Samples

The samples used in this investigation are: (1) concrete prisms with cement contents of 360 kg/m^3 (bridge mixture) and 420 kg/m^3 (standard mixture) for 3 aggregate types (virgin Sudbury aggregate, high deteriorated RCA, and low deteriorated RCA, (2) concrete cylinders with 360 kg/m^3 (bridge mixture) and 420 kg/m^3 (standard mixture) for 3 aggregate types (virgin Sudbury aggregate, high deteriorated RCA, and low deteriorated RCA, and (3) road barriers of high deterioration and low deterioration. Each sample type contains 3 specimens (1 set), with the exception of the road barriers in which there is only 2 low and 2 high deteriorated barriers. The cylinders were cast with studs placed in the top and bottom of the specimen to mimic concrete prisms. The road barriers were drilled and had studs placed on the face of the barriers. Each set of samples undergoing testing has a comparative set sealed with silane in an effort to mitigate expansion. The samples in the lab were tested for ASR as per CSA A23.2-14A (2014) and compared to the expansion in the road barriers in the field, believed to be affected by both ASR and freeze-thaw deterioration. The two mixtures (standard and bridge mixture) were chosen because the standard mixture for testing concrete prisms uses 420 kg/m^3 cement and it is believed that the bridge would have been made with 360 kg/m^3 cement. The coarse aggregate gradation for both virgin aggregate and RCA prisms and cylinders 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 and the alkalinity of the cement was raised to 1.25% as per the guidelines of the concrete prism test. Table 2 shows the difference between the standard and bridge mixture.

Table 2: Standard and Bridge Mix designs

	Standard Mixture	Bridge Mixture
Cement Content (kg/m3)	420	360
Water-cement ratio (%)	0.45	0.45
Coarse-fine aggregate ratio	60:40	60:40

*Corrections for absorption and moisture content of aggregates were included and alkalinity was raised to 1.25%

2.1.3 Cylinders

Since testing cylinders for expansion is not a normal practice, moulds that allow stud placement are not available. Thus, moulds needed to be made so that studs could be embedded into the top and bottom of the cylinders. Flattened studs were inserted into the center of 100 by 200 mm cylinders. Small plywood and acrylic plates were manufactured with female threaded binding barrels to precisely locate the stud as well as to provide a flat top surface to the cylinder. These plates were held in place at top and bottom with rubber bands after casting, as shown in Figure 4. Six of these moulds were created since each mixture contains three cylinders with silane and three cylinders without silane.

Figure 3: Separated Cylinder Mould


[redacted]

Figure 4: Completed Cylinder Mould

2.1.4 Road Barriers

The road barriers were placed on their backs, as shown in figures 1 and 2, to be prepped for stud placement. They are situated at an outdoor site provided by the MTO in the Toronto area. The studs were created using half-inch diameter, 2-inch length steel dowels with gage holes machined into them as per the instructions for the Whittemore Strain Gage. Holes were then drilled into the surface of the wall barriers 10 inches apart from each other using a jig, which represents the centre point of the Whittemore Strain Gage's measuring capability. The studs were placed roughly in the middle of the barriers and held in using non-shrink grout in order to ensure the top of the studs extended about 5 mm above the surface of the barriers for ease of measurement. The measurements are taken with an accuracy of 0.0001".

2.1.5 Silane-based sealer

Silane is a clear liquid coating that can be applied to concrete in an effort to repel water penetration. For each set of cast samples, a second set was cast of the same mixture and silane was applied to the samples. For the cast samples, the zero reading was taken after demoulding and then placed in a bucket over water at room temperature for 14 days for curing. This was done so the samples would not saturate, and lose alkalis before testing begun. After 14 days, silane was applied with a brush in two layers over two days and, as per the guidelines of the silane, were left out to dry for 7 days. In order to keep results consistent, the samples that did not receive silane treatment went through the same 14 day curing and 7 day drying procedure. The silane application for the road barriers also occurred over two days and were then covered with tarp for 7 days to allow for drying. The lab samples were then placed in the heat room at 38 degrees Celsius and 100% humidity as per the CSA standard for testing concrete prisms for ASR.

2.2 Experimental Procedures

2.2.1 Concrete Prism Test

The concrete prism test (CPT) was followed as per CSA A23.2-14A (2014) to determine expansion due to ASR, which requires a 60:40 ratio of coarse-to-fine aggregate. A water-cement ratio 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 hour curing, buckets were lined with cloth and the bars were placed inside, raised above water. The buckets were placed in a room maintained at 38 degrees Celsius and readings have been taken as per CSA A23.2-14A (2014).

2.2.2 Lab Cylinders

The cylinders followed the same preparation and testing procedures as the concrete prisms. This includes being placed into lined buckets, raised over water, and placed in a room maintained at 38 degrees Celsius and 100% humidity. The readings are also being taken as per CSA A23.2-14A (2014). Instead of the traditional length comparator used for concrete prisms, the measuring device used is an outside micrometer measuring to a precision of 0.0001”.

3 RESULTS AND DISCUSSION

3.1 Comparing virgin Sudbury aggregate with high and low deteriorated RCA

Lab data has been collected for 26 weeks using the CSA standard procedures for the CPT (CSA A23.2-14A) to compare results of the virgin Sudbury aggregate, high deteriorated RCA, and low deteriorated RCA in concrete prisms and cylinders. Figures 5a and 5b shows the difference in expansion between the three aggregates in the standard mixture (420 kg/m^3) and the bridge mixture (360 kg/m^3). It is consistent between the three aggregates that the bridge mixture yields slightly less expansion than the standard mixture in which the difference is an average of 0.006%. This is due to the larger amount of alkalis present in the standard mixture because of the larger quantity of cement. It is also consistent between the two mixture designs in that the samples with high deteriorated RCA expands slightly more than that of the low deteriorated RCA, both of which expand significantly more than the samples with virgin Sudbury aggregate. The difference between the high and low deteriorated RCA samples is only 0.006%, with the high deteriorated being 0.026% higher and the low deteriorated being 0.020% higher than the virgin Sudbury aggregate. The difference between the two degrees of deteriorated RCA is so minimal that it can be considered negligible. This suggests that when using Sudbury RCA, the level of deterioration that has already occurred does not affect the expansion results. The reason for this could be that when crushing, new faces of the aggregate are being exposed that have not yet reacted, thus causing expansion. The amount of expansion that would be caused from the faces that were already exposed and suffered from ASR would be far less than that of the new exposed faces, thus causing a similarity in the expansion between high and low deteriorated RCA. The reason for the increased expansion in RCA in comparison to the virgin Sudbury aggregate is likely due to the increase in alkalis. The increase in alkalis is because RCA consists of old cement paste in addition to the 360 kg/m^3 or 420 kg/m^3 of cement being used in the new mixture. All samples have already exceeded the acceptable limit of 0.04% well before the 1 year mark for the CPT as per the CSA, which is expected for Sudbury aggregate.

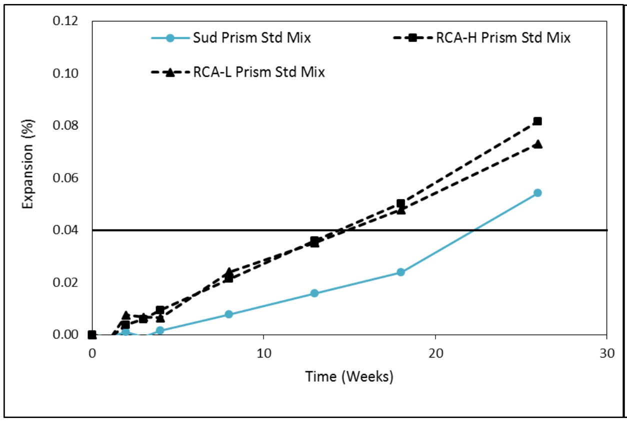


Figure 5a: Expansion of concrete prisms of standard mixture

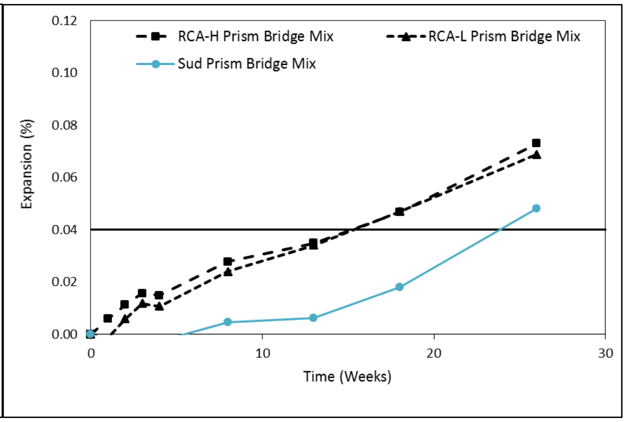
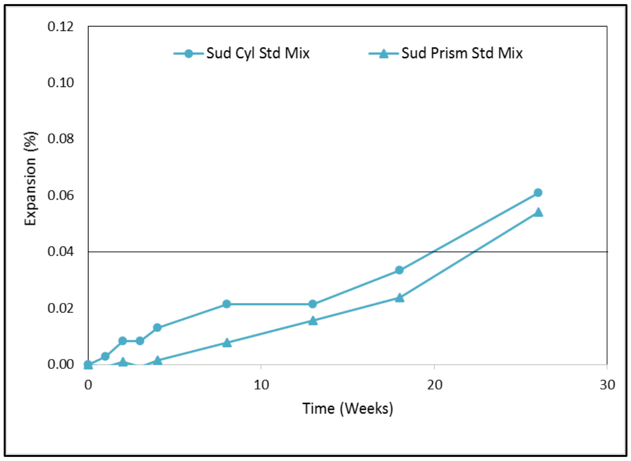


Figure 5b: Expansion of concrete prisms of bridge mixture

3.2 Comparing expansion results between concrete prisms and cylinders

In addition to the concrete prism results, 26-week data has also been collected from cylinders of the same mixtures. Shown in Figures 6a and 6b, the same trend follows with the cylinders in that the high deteriorated RCA expands at a slightly higher rate than the low deteriorated RCA, both of which expand significantly more than the virgin Sudbury aggregate. This further verifies that the expansion of the high and low deteriorated RCA is almost identical. It also further verifies that the additional alkalis present in Sudbury RCA results in high expansion than virgin Sudbury aggregate. It is also consistent within all three aggregate types that the cylinders expand at a slightly higher rate than the prisms at an average of 0.008%. The reason for the slight increase in expansion of cylinder can be attested to leaching of alkalis, due to the increased cross section of the cylinders, but it is not likely that the difference in expansion due to leaching would be noticeable at this time. Therefore, the expansion will continue to be monitored to determine the cause of the increased expansion.



Figures 6a: Expansion of Sudbury cylinders and prisms

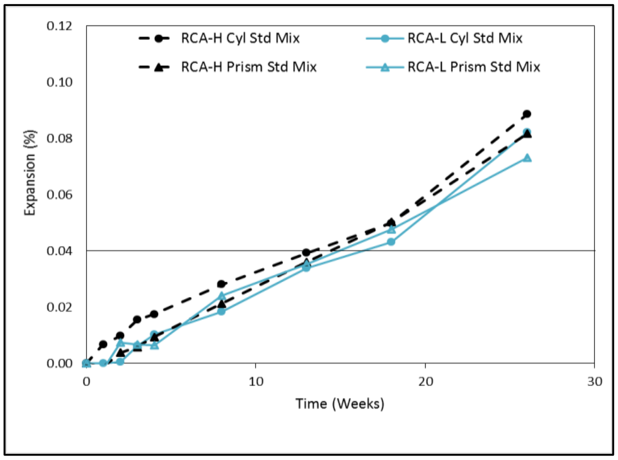


Figure 6b: Expansion of RCA prisms and cylinders

3.3 Effects of silane as a mitigation measure

Silane was applied to a set of all sample types in order to determine if it is a sufficient mitigation method for ASR. After 26 weeks, it has proven to be successful in all cases that were tested, which includes prisms and cylinders. In the case of the concrete prisms (shown in Figure 7a), the silane has proved to reduce the low deteriorated prisms by 0.020% and the high deteriorated prisms by 0.010% over 26 weeks. Figure 7b shows that there is also a reduction in expansion when silane was used on the cylinders. The silane caused very similar reduction results for samples cast with high deteriorated (0.018%) and low deteriorated (0.021%) RCA. The samples will be tested further to determine the efficacy of silane as a mitigation method for ASR.

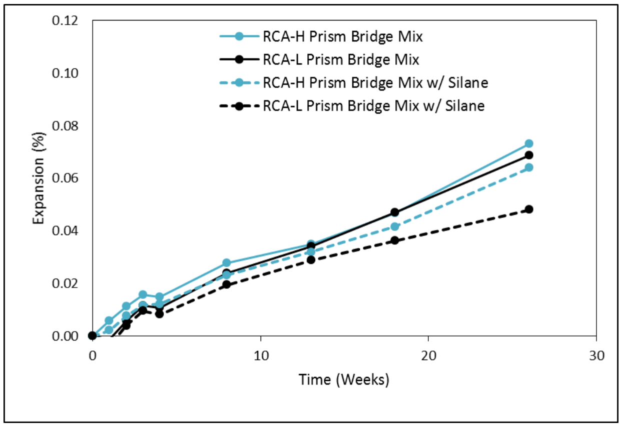


Figure 7a: Prisms with and without silane

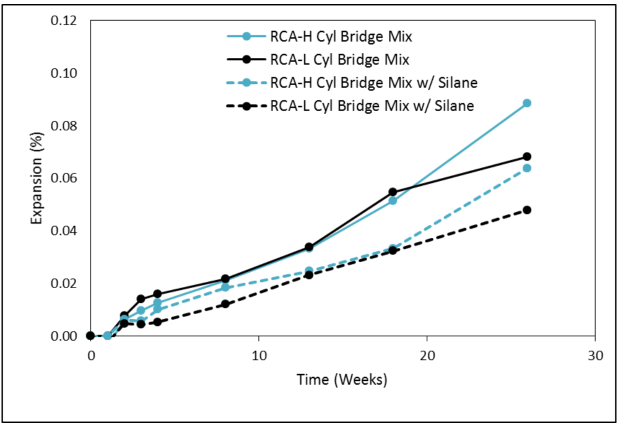


Figure 7b: Cylinders with and without silane

3.4 Expansion in Road Barriers

Expansion has been measured on the road barriers of high and low deterioration over the past year using the Whittemore strain gage. The results indicate that, after 1 year, there is no difference in expansion between the high and low deteriorated barriers as the expansion for both sets of barriers is roughly 0.013%. The measurements taken as the zero reading and week 51 were taken at the same temperature, 1 degrees Celsius, thus thermal expansion can be considered negligible. As expected, the expansion measured on the barriers are very minimal compared to the lab samples, even though the field specimens have been monitored for twice as long, because they are not exposed to severe (accelerated) conditions. The barriers also contain restrictions to expandion due to the surrounding concrete around the measuring studs. The barriers will continue to be monitored for years to come in an attempt to draw a correlation between lab and field data for structures affected by ASR. Further testing is being done on extracted concrete cores in order to correlate the data obtained from the lab to the field. The cores are being tested in the lab under the same conditions as the prisms and cylinders and results will be published at a later date.

4 CONCLUSIONS

1. Concrete containing alkali-reactive RCA produces higher expansion than concrete containing the original virgin gravel aggregate.
2. The level of deterioration that has previously affected the structure containing gravel reactive aggregate does not have a significant effect on its reactivity as an RCA. This suggests that the reaction occurs at the newly crushed faces of the aggregate.
3. Concrete cylinders expand at a higher rate than concrete prisms of the same mix design.
4. Silane-based sealers can be used to reduce expansion due to ASR and was found to be effective
5. Expansion of panels left on site was much slower than that of samples tested in lab at 38 degrees Celsius.

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