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UNDERSTANDING THE FACTORS AFFECTING EXPANSION DUE TO ALKALI-SILICA REACTION IN CONCRETE

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Abstract: Alkali-silica reaction is a chemical reaction resulting in expansion and disruption of concrete elements. The use of supplementary cementing materials (SCM) is one of the measures leading to reduction in expansion. The concrete prism test (CPT) is considered the most reliable lab test to evaluate efficacy of SCM. However, late expansions and cracking were observed in field for some aggregate/SCM combinations despite passing the 2-year expansion criterion of the CPT. A number of reasons, including alkali leaching from samples, could be behind this. In this research, the focus is to study the effect of sample geometry and testing temperature on alkali leaching and expansion. Cylinders and cubes were studied in addition to prisms at 38°C and 60°C using two aggregates of different reactivity: Spratt and Sudbury. Larger samples showed less leaching compared to standard prisms for both aggregates. For samples with SCM, cylinders casted with Sudbury showed higher expansion than prisms. However, with Spratt, they had similar expansions. This shows that the effect of sample geometry on expansion varies from one aggregate to another. The dependence of a particular aggregate on certain level of pore solution alkalinity to initiate expansion is an important factor that should be taken into consideration. In addition, results showed more leaching at higher temperature. The ultimate expansions of samples without SCM at 60°C were lower than the ones at 38°C. Also, the prisms two-year expansion values at 38°C were obtained using cylinders at 1 year at 60°C, which is a considerable saving in testing time.

1 INTRODUCTION

Alkali-silica reaction (ASR) is a chemical reaction that occurs between a form of reactive silica present in the aggregate and the alkaline pore solution of the concrete. This reaction will cause the formation of a gel that absorbs water and expands (Swamy 1992). Many preventive measures have been implemented to limit the expansion due to ASR. The addition of supplementary cementing materials (SCM) is one of the common measures that showed enhanced results (Shehata and Thomas 2000, Thomas et al. 2006). The results are based on the concrete prism test (CPT) described in the Canadian Standards, CSA A23.2-14A. This test is used to assess the reactivity of aggregates. An expansion limit of 0.040% at 1 year is specified in the standard above which the aggregate is considered reactive. However, many challenges are facing this test. First is the long testing time needed to obtain the results. To check the effectiveness of the SCM, an expansion below 0.040% should be obtained at 2 years. Many attempts are being made to reduce the testing period of the concrete prism test (Ideker et al. 2008, Liu and Mukhopadhyay 2015). Samples at 60ºC were tested in order to accelerate the reaction. However, it was found that more alkali leaching was happening at 60ºC (Ideker et al. 2008). In addition, some non-reactive aggregates at 38ºC showed expansion at 60ºC. Many correlations were made between the 13-week expansion of prisms at 60ºC compared to the actual prisms at 52 weeks for control samples (Fourier et al. 2004, Ideker et al. 2008). Fournier found that the accelerated test gives same diagnostic results as the standard CPT in 88% of the cases. However, Ideker showed that expansions after 13 weeks tend to be reduced at 60ºC compared to the standard prisms at 1 year.

Another challenge that is facing the concrete prism test is the excessive alkali leaching. Due to the small size of the prisms compared to the field, more leaching is occurring in the laboratory samples (Thomas et al. 2006, Ideker et al. 2012). Bérubé found that the larger the diameter of the cylinders or the lower the air/concrete ratio the less leaching will occur leading to higher expansion (Bérubé et al. 2012). Many attempts are being made in order to reduce the leaching of the prisms such as the application of silane-based sealer, plastic sleeve or aluminum foil protection (Rivard et al. 2006, Bérubé et al. 2012). However, none of the methods was able to reduce leaching and increase expansion at the same time. Many researches compared expansions of concrete prisms with exposure blocks from the field (Fournier et al. 2008, Ideker et al. 2012). At 10 years, Ideker found good correlation between the expansions of the CPT at 2 years and the samples in the field. However, at later ages, the leaching of the prisms was more revealed leading to lower expansion compared to the field blocks. Hence, it is important to test blocks in the field under environmental conditions to validate the laboratory results. The alkali leaching as well as the long testing time of the concrete prism test are the main challenges that are being investigated to enhance the results obtained in the lab and to obtain better correlations between field and lab samples.

2 EXPERIMENTAL DETAILS

2.1 Materials

2.1.1 Aggregates

In this study, two coarse aggregates of different reactivity were tested: Sudbury and Spratt. The fine aggregate used is a non-reactive natural sand. The bulk relative density, absorption and expansion of the different aggregates are summarized in Table 1. The expansion is obtained based on results from the concrete prism test described in CSA A23.2-14A. The expansion limit at 1 year is 0.040% below which the aggregate is considered non-reactive.

Table 1: Aggregates Properties

Aggregate	Sudbury	Spratt	Non-Reactive Sand
Bulk relative density	2.552	2.691	2.538
Absorption (%)	0.56	0.52	1.30
Expansion at 1 year (%) (CSA A23.2-14A)	0.170	0.211	-

2.1.2 Cementitious Materials

The cement used is a Type GU cement (GU PC) with 0.99% Na_2O_e. Two supplementary cementing materials were implemented in this research: low calcium fly ash (FA) and slag. The chemical compositions of the cementitious materials are provided in Table 2.

Table 2: Chemical compositions of the cementitious materials

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O_e	LOI
GU PC	19.54	5.21	2.16	62.39	2.39	4.03	0.99	2.36
Fly Ash	57.0	23.4	3.5	9.5	1.0	0.1	2.89	0.59
Slag	37.0	8.2	0.5	38.5	10.5	2.7	0.67	2.1

2.2 Experimental Procedure

2.2.1 Sample Preparation

Three different sample shapes were investigated: prisms (75x75x285 mm), cylinders (ø 100 mm by 285 mm) and 150 mm cubes. The coarse aggregate portion is composed of three equal masses of materials size between 19.5 mm to 13.2 mm, 13.2 mm to 9.5 mm and 9.5 mm to 4.75 mm. The coarse to fine aggregate ratio is 60:40 by mass. A water to cement ratio of 0.42 is used. The cement content is 420 kg/m^3. The alkali content is boosted to 1.25% by weight of cement by adding sodium hydroxide. The procedure followed is presented in CSA A23.3-14A. The prism molds used are similar to the ones specified in the standard. Since there are no standard test for cylinders and cubes, their molds were fabricated at Ryerson's lab and are shown in Figure 1.

(a) (b)

Figure 1: Molds for (a) cylinders and (b) cubes

The cubes were casted in 3 layers where each layer was rodded 25 times similar to the prisms. The cylinders were casted in 4 layers and each layer was rodded with 25 strokes to allow better consolidation along the height. After casting, the samples were put in the curing room for 24 hours and then demolded the next day. Containers were made ready by aligning an absorbent cloth on their walls. The clothes were made wet before putting the samples in. The samples were elevated by around 4 cm above the bottom of the containers and put above water. The pails for prisms and cylinders fit 3 samples at a time as for the cubes one sample is put in each container. The pails and containers used to put the samples in are shown in Figure 2.

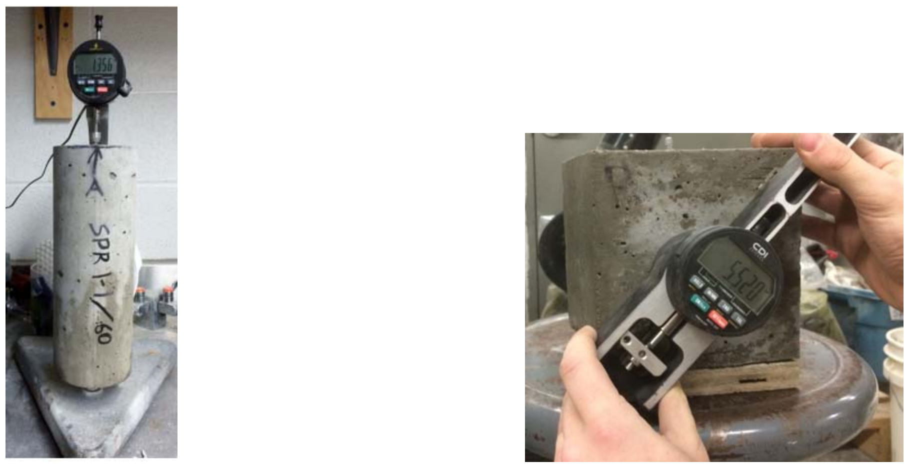
(a) (b)

Figure 2: (a) Pails for the prism and cylinder samples (b) containers for cube samples

Each set of samples is composed of 3 prisms, 3 cylinders and 3 cubes. Two sets of the same mix were prepared. One is put in a heat room at 38ºC and the other set in an oven at 60ºC.

2.2.2 Expansion Measurements

The zero reading was taken before putting the samples at their designated temperatures. Measurements were made after 1, 2, 4, 8, 13, 18, 26, 39, 52 weeks and then once every 3 months until 2 years. The cylinders were measured the same way as the prisms using the length comparator. As for the cubes, a demec style digital strain gauge was used. The pins are put diagonally on two adjacent faces of the cubes and they are 150 mm apart. The average expansion of three samples of the same shape at the same temperature is presented in this paper. The length comparator and the strain gauges used for the different samples are shown in Figure 3.



(a) (b)

Figure 3: Measurements of (a) cylinders and (b) cubes

2.2.3 Leaching Measurements

Leaching measurements were performed at 1.5 years to obtain the amount of alkalis that leached out from the samples. To do so, the volume of the solution at the bottom of the containers was measured and then a 10 mL sample was collected. The concentrations of Na^+ and K^+ in the solution were obtained by flame photometry. The amount of leached Na^+ and K^+ ions were measured as concentration then converted to Na_2O_e mass taken as a percent of the initial 1.25% boosted alkalis by Portland cement mass.

3 RESULTS AND DISCUSSION

3.1 Testing at 38 ºC

The 1-year expansion of prisms, cylinders and cubes at 38ºC for Sudbury and Spratt without SCM are presented in Figure 4.

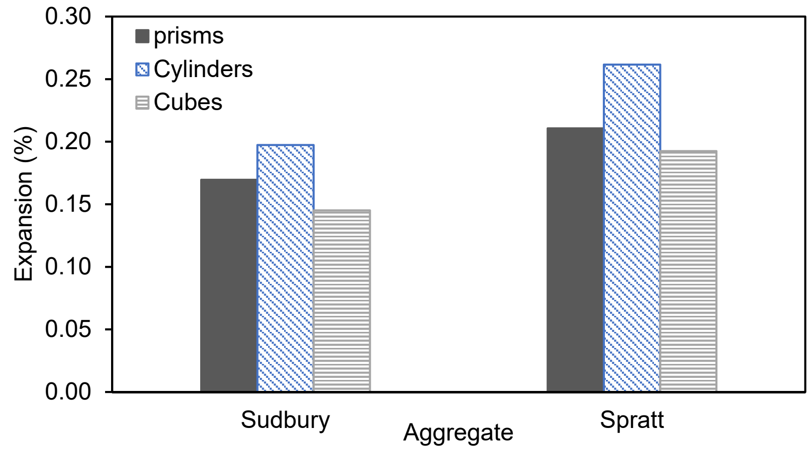


Figure 4: 1-year expansion of Sudbury and Spratt without SCM at 38ºC for prisms, cylinders and cubes

With both aggregates, the expansion of the cylinders is higher compared to that of the prisms. This is obtained with the samples without SCM. As for the samples with SCM, the expansion data of the Sudbury samples with 15% FA and 25% slag are shown in Figure 5.

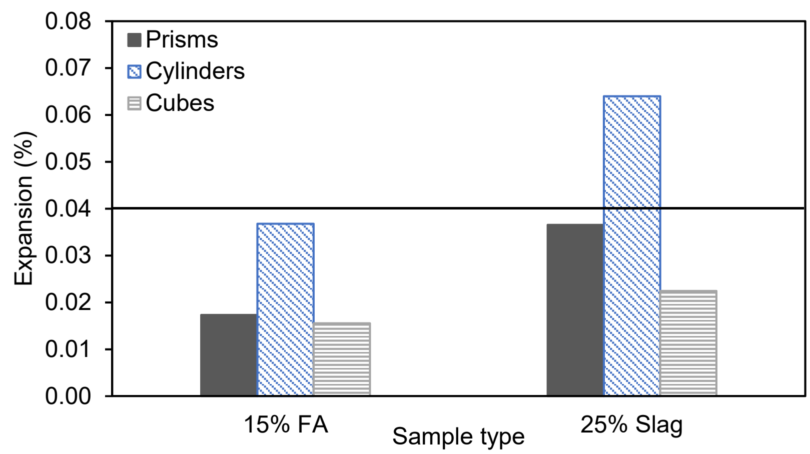


Figure 5: 2-year expansion of Sudbury with SCM at 38ºC for prisms, cylinders and cubes

The cylinders showed much higher expansion than the prisms and cubes. For the samples with 15% FA, the cylinders were about to fail with an expansion equal to 0.037% as compared to only 0.017% for the prisms. In addition, the cylinders casted with Sudbury and 25% slag passed the expansion limit of 0.040% as compared to prisms which had an expansion below the limit. At the same age and temperature, cylinders casted with Sudbury aggregate with and without SCM have higher expansion than prisms. As for the Spratt samples with SCM, the expansion at 38ºC at 2 years for samples with FA and 1.5 years for samples with slag are shown in Figure 6. The 2-year expansion of samples with slag is yet to be measured.

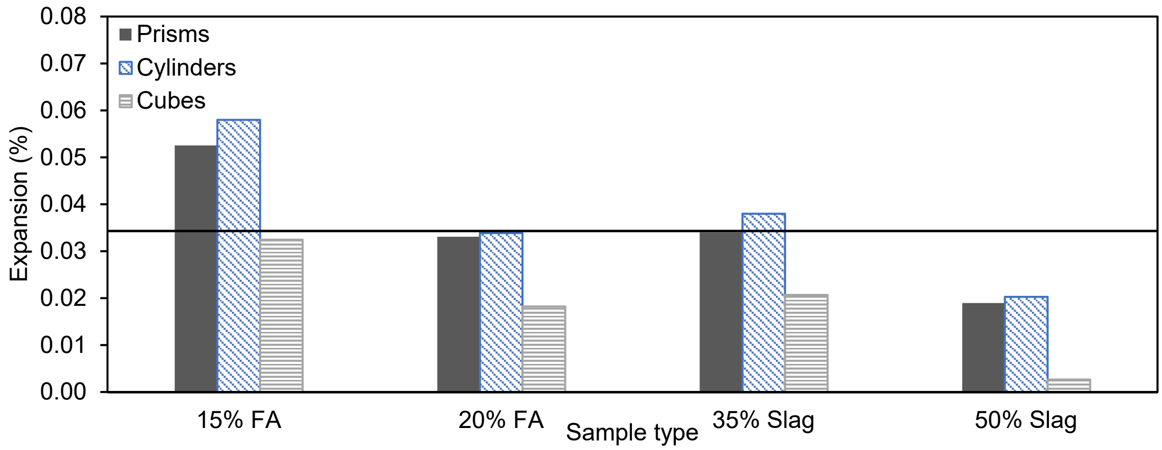


Figure 6: 2-year expansion of samples with FA and 1.5-year expansion of sample with slag at 38ºC for prisms, cylinders and cubes casted with Spratt

Prisms and cylinders casted with Spratt at 38ºC have the same expansions with all the tested SCM. For the Spratt with 15% FA, prisms and cylinders both passed the expansion limit of 0.040%. At the same age, same expansion was obtained for prisms and cylinders casted with Spratt as opposed to the behavior observed with the Sudbury aggregate. To understand these findings, alkalis leached from the samples to the bottom of the containers were measured for different sample geometries at 38ºC. The results are presented in Figure 7 which compares the alkalis leached at 38ºC in prisms with that of cylinders after 1.5 years. The shaded markers correspond to the sample without SCM for the specified aggregate.

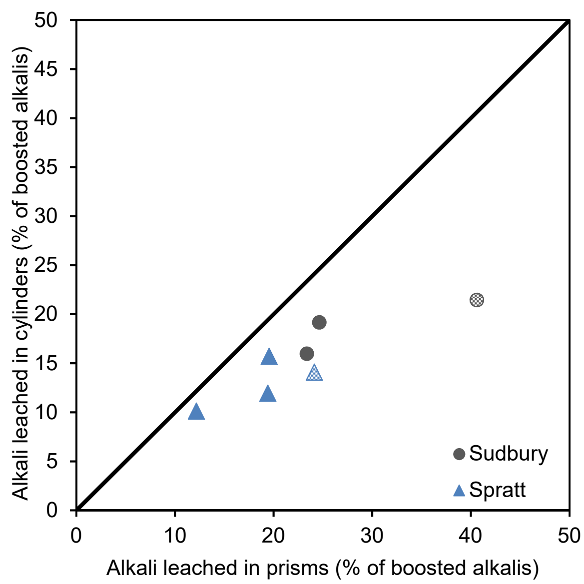


Figure 7: Comparison of alkali leaching at 1.5 years at 38ºC between prisms and cylinders for Sudbury and Spratt aggregates

Figure 7 shows that more leaching is occurring with prisms compared to cylinders with both aggregates leading to the conclusion that larger samples reduce the amount of leaching. It is expected that the expansion will be higher for larger samples since more alkalis are available for the formation of ASR gel. For Sudbury aggregate, the expansion of cylinders at 38ºC was higher than that of the prisms for the control as well as for the samples with SCM. However, with Spratt, the cylinders and prisms had similar expansions at 38ºC for the samples with SCM. Although the leaching was higher with the prisms, however, Spratt aggregate was not affected by the change in the alkali level as compared to Sudbury. It seems that Sudbury aggregate is more sensitive to changes in alkalinity resulting in the observed difference in expansion. This might be due to the fact that Spratt reacts faster and consumes the alkalis before they leach as compared to Sudbury, a slowly reactive aggregate. Sudbury showed higher leaching results compared to Spratt. The prisms and cylinders casted with Sudbury showed a leaching of 41% and 21%, respectively as compared to 24% and 14% for Spratt (shaded markers in Figure 7). In addition to this, it was found that Sudbury aggregate releases more alkalis to the pore solution (Bérubé et al. 2002). Hence the higher alkali leaching in case of Sudbury could be due to: (i) alkalis contributed from the aggregates, and (ii) slow reaction of Sudbury leaving more alkalis in pore solution of the concrete that is “free” to be leached. It should be noted also that although the results showed lower leaching for the cubes compared to cylinders and prims, however the expansion of cubes was still lower than the cylinders at 2 years. The reasons behind this are still not clearly understood but it could be due to the restraints effect that might occur in the cubes.

3.2 Testing at 60ºC

3.2.1 Expansion of Sudbury and Spratt Aggregates without SCM

Expansion of prisms, cylinders and cubes were measured for Sudbury and Spratt samples without SCM. The data obtained at 6 months and 1 year are presented in Figures 8 and 9 for Sudbury and Spratt, respectively at 38ºC and 60ºC.

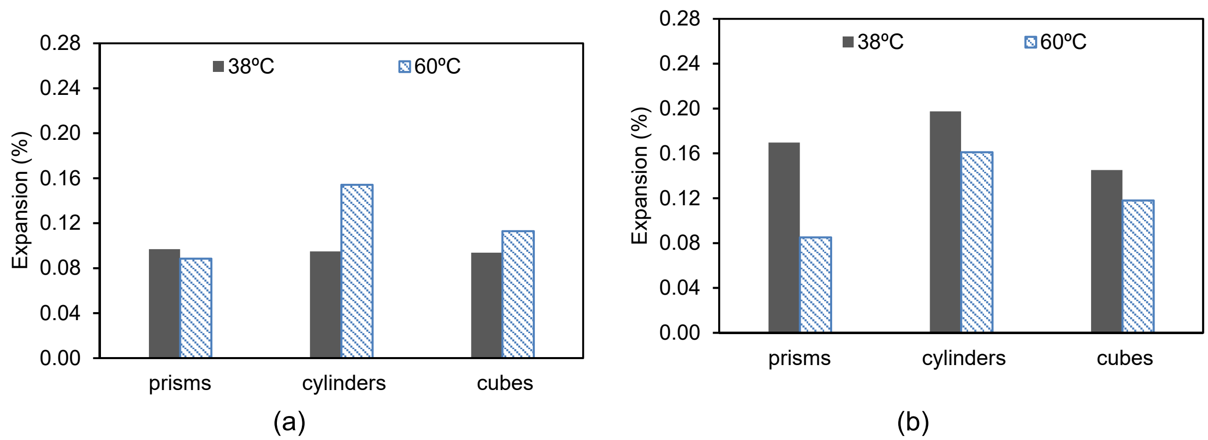


Figure 8: Expansion of Sudbury aggregate at 38ºC and 60ºC at (a) 6 months and (b) 1 year

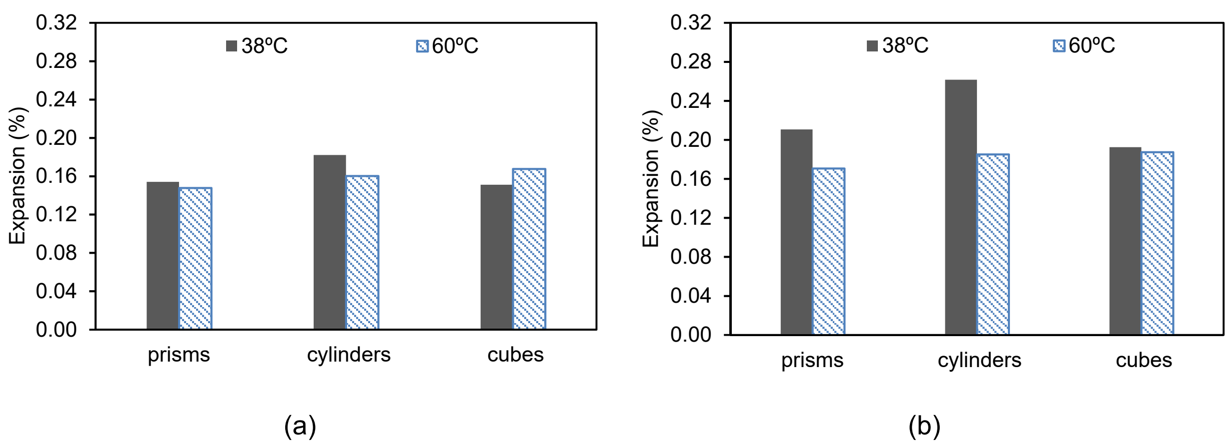


Figure 9: Expansion of Spratt aggregate at 38ºC and 60ºC at (a) 6 months and (b) 1 year

Expansions of Spratt at 6 months were the same at 38ºC and 60ºC. However, cylinders containing Sudbury showed higher expansion at 60ºC compared to 38ºC. In addition, at 1 year, it is clear for both aggregates that the ultimate expansions at 38ºC are higher than the expansions at 60ºC for all the different sample shapes. Leaching of alkalis from the samples at 60ºC was measured at 1.5 years and compared to the leaching of the same samples tested at 38ºC. Results are shown in Figure 10.

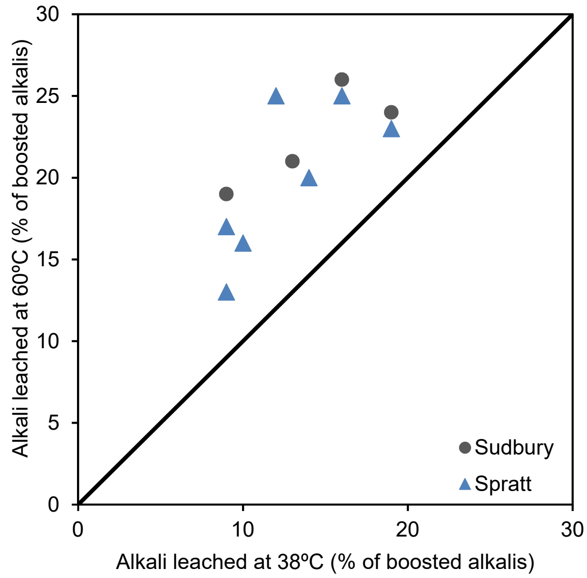


Figure 10: Comparison of alkali leaching at 1.5 years between 38ºC and 60ºC

The samples at 60ºC leached more than the samples at 38ºC for both aggregates and for all the different sample geometries. This is due to the higher diffusivity of alkalis with increased temperature (Lindgard et al. 2012). The rate of alkali leached is increased at 60ºC lowering the alkalinity of the pore solution faster than the samples at 38ºC. This explains partly the fact that Spratt and Sudbury control samples showed lower ultimate expansions at 60ºC compared to 38ºC. This could also be due to the effect of temperature on the gel viscosity exerting less pressure at higher temperatures (Swamy 1992). In addition, it was found that there is a decrease in pore solution alkalinity at 60ºC due to the higher solubility of the ettringite (Fournier et al. 2004).

3.2.2 Expansion of Sudbury and Spratt Aggregates with SCM

Samples with FA and slag at different replacement levels were also measured for expansion. The data obtained at 1 year and 2 years for samples with 15% FA are presented in Figures 11 and 12 for Sudbury and Spratt, respectively.

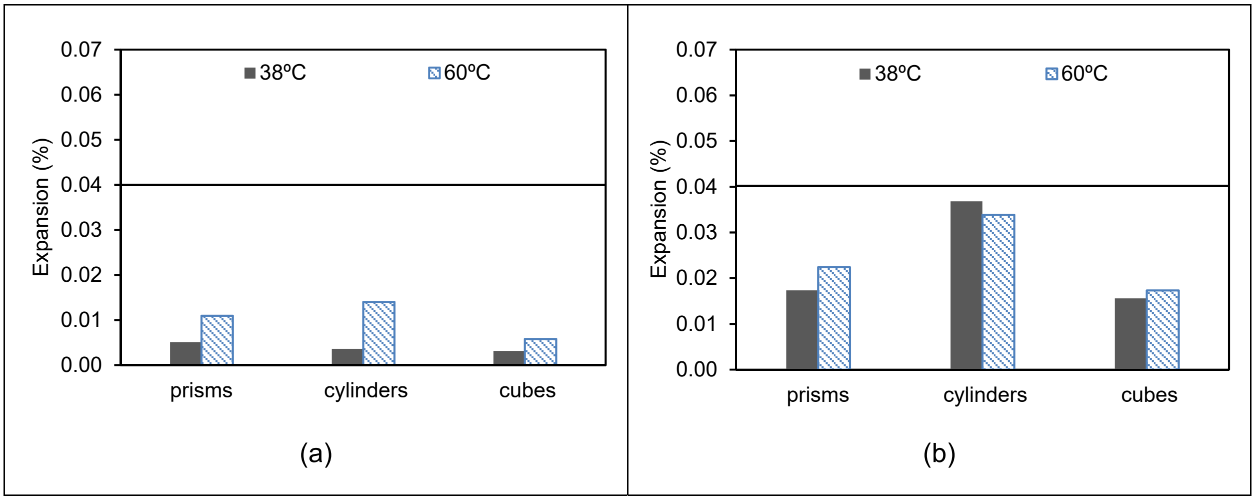


Figure 11: Expansion of Sudbury aggregate with 15% FA at (a) 1 year and (b) 2 years

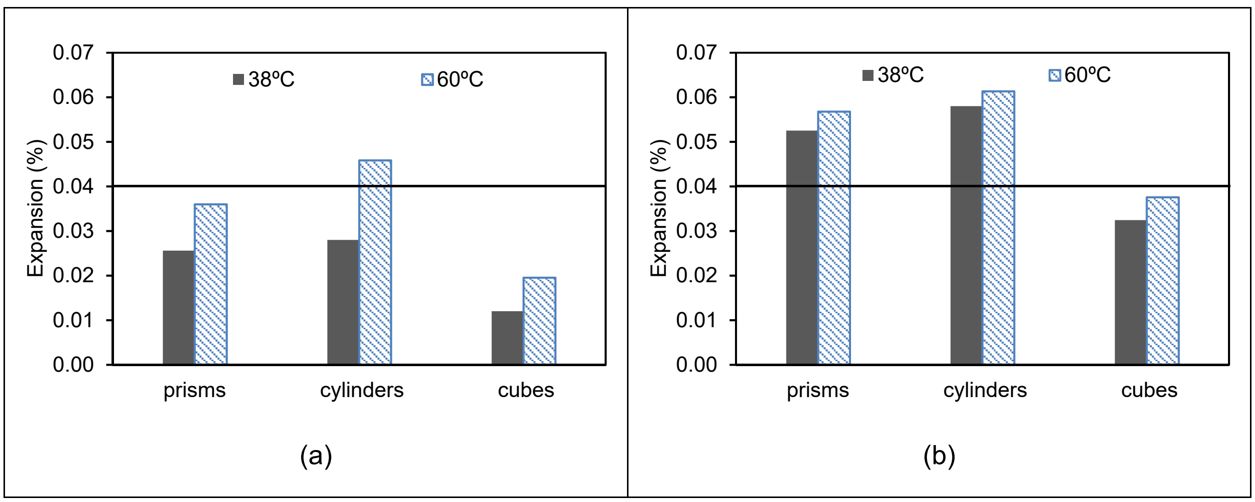


Figure 12: Expansion of Spratt aggregate with 15% FA at (a) 1 year and (b) 2 years

According to CSA A23.2-27A, replacing cement by 15% FA is supposed to reduce the 2-year expansion of concrete prisms to below 0.040% when using the CPT with Sudbury aggregate but not with the highly reactive aggregate, Spratt. This was found to be the case as shown in Figures 11-b and 12-b. Looking at the cylinders expansions at 60ºC at 1 year, same conclusions are drawn (Figures 11-a and 12-a). Sudbury cylinders had an expansion lower than 0.040% as compared to the Spratt cylinders which showed an expansion higher than 0.040% at 1 year at 60ºC. Table 3 shows the expansion of prisms at 38ºC at 1 year and 2 years for the control samples and samples with SCM, respectively. These expansions are compared to the expansions of the cylinders at 60ºC at 6 months and 1 year, respectively to see if testing at 60ºC can reduce the testing period by 50% when cylinders are used.

Table 3: Comparison of prisms expansion at 38ºC and cylinders expansion at 60ºC

Sample type		Expansion of cylinders at 60ºC*	Expansion of prisms at 38ºC**	Difference in expansion (%)	Pass/Fail Criterion
Sudbury	Control	0.154	0.170	0.016	Fail/Fail
	15% FA	0.014	0.017	0.003	Pass/Pass
	25% Slag	0.022	0.037	0.015	Pass/Pass
Spratt	Control	0.160	0.211	0.050	Fail/Fail

Sample type	Expansion of cylinders at 60ºC*	Expansion of prisms at 38ºC**	Difference in expansion (%)	Pass/Fail Criterion
15% FA	0.046	0.053	0.007	Fail/Fail
20% FA	0.032	0.035	0.001	Pass/Pass
35% Slag	0.041	0.037	0.004	Fail/Pass

*Expansion of cylinders for the control samples is at 6 months and for the samples with SCM at 1 year.

**Expansion of prisms for the control samples is at 1 year and for the samples with SCM at 2 years.

Both expansions obtained from the prisms at 2 years at 38ºC and the cylinders at 1 year at 60ºC with SCM showed a pass/pass or fail/fail relationship except the Spratt sample with 35% slag. This was due to the fact that the expansion of the prisms was taken at 1 year and 9 months because they did not reach 2 years at the time of writing the paper. However, the expansion of the prisms was very close to fail with a value of 0.037%. In addition, although there was a pass/pass relationship for the Sudbury samples with 25% slag, however, the expansion of the cylinders at 60ºC at 1 year was much lower than the prisms at 38ºC at 2 years. The reasons for this behavior is still under investigation. In conclusion, the 2-year expansion of prisms with SCM at 38ºC can be obtained with the cylinders in a shorter time at 60ºC. Although at 60ºC, more leaching is occurring, but the cylinders leach less compared to prisms. In addition, the increase in temperature will accelerate the ASR reaction. Hence, by reducing leaching and accelerating the reaction, the same conclusions obtained with the standard prisms at 2 years at 38ºC can be reached with the cylinders at 60ºC at 1 year. The testing time is reduced significantly with the use of cylinders at 60ºC. However, it should be noted that more samples need to be tested to confirm the applicability of the above finding to a wide range of aggregate/cementing blends.

4 CONCLUSIONS

The main conclusions that can be obtained from this study are as follows:

1. Larger samples as well as lower temperatures will lead to reduction in alkali leaching.
2. Higher expansion can be obtained with cylinders compared to prisms at the same age and temperature due to reduced leaching however it depends also on the aggregate type.
3. Sudbury aggregate showed higher expansion with the cylinders compared to prisms. However, this was not the case with the Spratt aggregate. The dependence of the aggregate on a certain level of pore solution alkalinity might also affect expansion.
4. Samples without SCM showed lower ultimate expansions at 60ºC as compared to 38ºC.
5. The 2-year expansion of the standard prisms casted with SCM at 38ºC using the CPT described in CSA A23.2-14A can be obtained in a shorter duration with the cylinders at 60ºC at 1 year.

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