MITIGATING ALKALI-SILICA REACTION WHEN USING HIGH-ALKALI CEMENTS

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Abstract

Until 2009, the Canadian CSA A23.2-28A standard practice limited the alkali content of the cement that could be evaluated together with SCMs in concrete prisms to a maximum of 1.0% Na_2O_{eq}. This somewhat arbitrary limit was based on a survey of Canadian cements in the 1990s. However, currently many North American cements now have higher alkali contents. ASTM C1293 and C1567 have no such restriction and the equivalent RILEM AAR-3 test method allows use of cements with alkali equivalents of up to 1.2%. In the initial laboratory study, concrete prisms were cast and monitored using two different reactive aggregates and different levels of fly ash and slag recommended for mitigation in the CSA A23.2-27A standard practice. Three cements with 0.97 to 1.11% Na_2O_{eq} were used. For the concrete prism tests, the alkali contents of the cements were either (a) increased to 1.25% Na_2O_{eq}, as per the standard, or (b) were increased by 0.25% Na_2O_{eq}. In addition, in 2007 a series of large outdoor exposure concrete blocks (along with additional concrete prisms stored at both 38 and 60^{o}C) were cast from 32 mixtures with cement alkali equivalents ranging up to 1.22%.

Keywords: cement alkalies, mitigation, concrete prisms, outdoor exposure

1 INTRODUCTION

Alkali-silica reactive aggregates may be used in concrete if sufficiently mitigated. Sufficient levels of appropriate sources of supplementary cementitious materials (SCMs) have been shown to prevent deleterious expansion [1-5]. However, testing potential mitigation measures may require significant lead time. An alternative approach, CSA A23.2-27A, "Use of Supplementary Cementing Materials for Counteracting Alkali-Silica Reaction," incorporates long-term performance data from laboratory prisms, outdoor exposure tests, and structures. It limits maximum alkali contents of concrete and provides recommendations on the minimum dosages of supplementary cementing materials (SCMs) for use with reactive aggregates of different reactivity levels. CSA A23.2-27A was introduced in 2000 and updated in 2004 and 2009. It is the model for AASHTO PP-65 and a practice under development at ASTM.

However, until 2009, the Canadian concrete prism test, CSA A23.2-14A (similar to ASTM C1293 and RILEM AAR-3), and the CSA A23.2-28A standard practice limited the alkali content of the cement that could be evaluated together with SCMs in concrete prism tests to a maximum of 1.0% Na_2O_{eq}. This limit was based on a survey of available Canadian cements around 1990. The ASTM C1293 and C1567 test methods

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have no such restriction. Since in both A23.2-14A and A23.2-28A, the alkali content of the cement used in concrete prism tests is artificially raised to 1.25% using NaOH dissolved in the mix water to accelerate expansion and to compensate for alkali leaching during storage, cements with initial alkali contents slightly greater than 1.0% may not cause grossly unrepresentative expansions, but as alkali levels rise, these cements may require higher levels of SCMs to control expansion when used in structures where alkalies will not be leached.

Reactive aggregates and high-alkali cements have performed well in service. The Lower Notch Dam in Ontario was built in 1970 with reactive greywacke-argillite aggregate and 1.08% Na_2O_{eq} alkali cement in combination with 20% and 30% Class F fly ash. Mortar bar tests with the same aggregates found that 20% Class F fly ash was sufficient to mitigate deleterious expansions [3, 4]. The dam is still performing well after 40 years with no signs of ASR, as observed during a 2010 site visit by two of the authors [4].

The work described here was undertaken to determine whether higher replacements of cements with SCMs were needed for mitigation of ASR when cements had alkali contents greater than 1.0%. This work lead to changes to the CSA A23.2-27A standard practice in 2009 that now allow use of portland cements with up to 1.15% Na_2O_{eq} for moderately reactive aggregates. In addition, any ASR aggregate can be mitigated with SCMs using portland cements with up to 1.25% Na_2O_{eq} provided that the level of mitigation recommended in the standard practice is raised by one level.

2 MATERIALS AND METHODS

2.1 General

The test program is divided into a laboratory study and an outdoor exposure study. In the laboratory study, to assess the adequacy of the required levels of SCM replacement for cements having alkali contents greater than 1.0%, specimens were cast with high-alkali cements using the CSA A23.2-14A (similar to ASTM C1293) concrete prism test and the CSA A23.2-25A (modified by CSA A23.2-28A, similar to ASTM C1567), accelerated mortar bar test, with both the SCM levels required by the CSA A23.2-27A standard practice as well as with one higher level of SCM. In addition, in 2007, a series of large outdoor exposure concrete blocks (along with additional concrete prisms stored at both 38 and 60^oC), were cast from 32 mixtures with cement alkali equivalents ranging to 1.22% and expansions up to 4 years have been monitored.

2.2 Materials and mixture proportions

For the laboratory study, two reactive coarse aggregates were used. The highly reactive Spratt aggregate is a siliceous limestone from the Bobcaygeon Formation around Ottawa, Ontario. The moderately reactive Sudbury aggregate is a partially crushed gravel with argillite, greywacke and sandstone from Precambrian Huronian Supergroup around Sudbury, Ontario [5]. A non-reactive natural sand from the Millcreek pit in Ontario was used.

Three cements with alkali contents of 0.97%, 1.08%, and 1.11% Na_2O_{eq} were used for the concrete prism tests and the 1.08% alkali cement was used for the accelerated mortar bar tests. The fly ash was a CSA Type CI ash from Alberta. Due to changes adopted in 2010, this fly ash is now considered a Class F ash in CSA A3000, but the replacement levels were selected based on the original CI ash designation. Replacement levels 5% lower would have been used if it had been designated a Class F fly ash. The ground granulated blast-furnace slag was from Ontario and would likely be a Grade 80 according to ASTM C989. The compositions of the cementitious materials are provided in Table 1 (left side of Table 1).

The required levels of SCMs according to CSA A23.2-27A were determined using an assumed exposure condition of humid air, buried or immersed and an assumed design service life of 5-75 years. These criteria led to the selection of 35% fly ash and 50% slag cement to mitigate deleterious expansion for the

Spratt aggregate concrete mixtures, as well as 30% fly ash and 35% slag cement for the Sudbury aggregate mixtures. In addition, 40% fly ash and 60% slag were also used with Spratt aggregate as the next additional level of mitigation. Similarly, for Sudbury aggregate, 35% fly ash and 50% slag replacements were also used. The same initial fly ash and slag cement replacement levels were used for the mortar bar tests. Based on the expansions obtained, some additional replacement levels were also tested.

For the concrete prism mixtures, two different alkali loadings were used. For Series A mixtures, the alkali content of the cement was increased to 1.25% Na_2O_{eq}, as per the standard. For Series B, the cement alkali content of the cement was increased by an additional 0.25% Na_2O_{eq}. After demolding at 1 day, length and mass of each prism was measured and each set of prisms was sealed in a 22L polyethylene pail over water, and with wicking material on the pail sides. The pails were placed in a 38^{o}C room. One day prior to each measurement, pails were cooled to 23^{o}C, and after length and mass measurements, pails were re-sealed and replaced in the 38^{o}C room.

CSA A23.2-28A (ASTM C1567) mortar bars were demolded at one day, then immersed in water and then heated to 80^{o}C. The CSA method uses a w/cm of 0.50 for crushed aggregates whereas ASTM C1567 uses w/cm = 0.47. At 2 days of age, initial length and mass measurements were made at 80^{o}C, and bars were immersed in 1N NaOH solution preheated to 80^{o}C. Subsequent measurements were made at 80^{o}C.

2.3 Additional Exposure Block Program and Concrete Prism Tests

As part of longer term confirmation of this study, in cooperation with Natural Resources Canada, 32 large air-entrained concrete blocks were cast from similar mixtures and placed in outdoor exposure in Ottawa in 2007. This is part of a larger outdoor exposure program [6]. In large concrete blocks, there is little concern with alkali leaching, but the ambient exposure conditions in Ottawa require longer times for deleterious ASR expansion and cracking to occur. As shown by Hooton et al [7], concrete exposure blocks incorporating the highly-reactive Spratt limestone and stored outdoors in nearby Kingston Ontario took 8-10 years to attain the same expansion as 38^{o}C concrete prisms after 2 years.

Blocks were 400 x 400 x 700mm in size. For monitoring length changes, 75-mm long stainless steel threaded studs were partially embedded in the concrete specimens on the tops and sides. Length measurements are being taken on the longitudinal axis on the top and on both sides of each block. After 7 days in the forms covered with wet burlap, the blocks were de-moulded and transported to the outdoor exposure site located in Ottawa, Canada. From the same air-entrained mixes, 2 sets of concrete prisms were also cast. One set was transported to the University of Toronto and placed in moist exposure at 38 ^{o}C, and the other set was tested at Natural Resources Canada in accelerated 60^{o}C moist exposure (essentially the same as the RILEM AAR-4 test).

For the outdoor exposure study, air entrained (5-7% air), 420 kg/m^3 binder content (w/cm = 0.36-0.42) concrete mixes were cast with Spratt and Sudbury aggregates using three different cements as shown in Table 1 (right side of Table 1). Mixes with 0.96 and 1.10% alkali cements were used without added alkali, while mixes containing the 1.22% alkali cement had alkali levels boosted to 1.25% through the addition of NaOH pellets to the mix water. Different samples but the same sources of fly ash and slag were used as in the lab study, with compositions also shown in Table 1. SCM replacement levels used for Spratt were 0, 30 and 35% fly ash with the 0.96% alkali cement, and 0, 30, 35, and 40% fly ash and 35 and 50% slag with the 1.10 and 1.22% alkali cements. For the Sudbury aggregate, 0, 25 and 30% fly ash were used with the 0.96% alkali cement, 0, 25, 30, and 35% fly ash and 30, 40 and 50% slag with the 1.10 and 1.22% alkali cements.

3 RESULTS

The 2-year 38°C laboratory concrete prism expansions are presented in Table 2 for both the Spratt aggregate mixtures and for Sudbury aggregate mixtures. Fourteen day, accelerated mortar bar expansions are provided in Table 3.

The agreement between concrete prism expansions, using a 2-year expansion limit of 0.040%, and the accelerated mortar bar expansions, using a 14-day expansion of 0.10% as per CSA A23.2-28A (equivalent to ASTM C 1567), are shown in Table 4. In Table 4, 'PASS' indicates expansions are less than the limit for each test, and 'FAIL' indicates expansions above the limit.

Expansions of the concrete prisms cast from the outdoor exposure block mixtures are shown in Table 5 for the 38°C prisms at 2 years, in Table 6 for the 60°C prisms at 6 months, while Table 7 is giving the average block expansions (top and sides of the blocks) after 4 years outdoor exposure. An earlier exposure block study at the same exposure site also used these same two aggregates to evaluate the efficacy of fly ash and slag in reducing expansion due to ASR [10]. In that study, the fly ash and the high-alkali cement were from different sources, while the slag was from the same plant as for this study (Table 8). Expansions after both 4 and 12 years of outdoor exposure, obtained from the second author, are shown in Table 9. In Tables 6, 7 and 9, expansions greater than 0.040% are shown in bold.

4 DISCUSSION

As shown in Table 2, for each cement tested, there was very little difference between the concrete prism expansions in the A (1.25% alkali) and B (alkalies boosted to 1.33% or 1.36% alkali) test series. Therefore, from these results, it would appear unnecessary to increase the cement alkali content above 1.25%. However, the extent of alkali leaching from the concrete prisms during the 2-year test period is a critical factor and can vary between laboratories; therefore, to allow for this, it would be more conservative to adopt raising the alkali in the mixes to 0.25% above that in the cement used (i.e. the B condition). All of the dosages of fly ash or slag cement were effective in controlling expansions below 0.040% according to the concrete prism test for both aggregates; however, the 35% slag mix with the 1.11% alkali cement and the Sudbury aggregate appears more "marginal" as it expanded higher than the others and close to the limit in both Series A and B tests (0.037 and 0.036%, respectively). Given test variability, it could have exceeded 0.040% in another laboratory.

Table 3 shows that for the Spratt aggregate, both 40% fly ash and 35% fly ash produced mortar bar expansions below 0.10% at 14 days. However, at least 55% slag cement was needed to control expansions; this was higher than the 50% required in CSA A23.2-27A and by the concrete prism results in given Table 2. In previous studies, 50% slag was sufficient to reduce Spratt expansions to less than 0.10% at 14 days [1, 8, 10, 11]. For the Sudbury aggregate, Table 3 indicates that at least 45% slag cement is needed to control expansions (higher than the 35% indicated in CSA A23.2-27A and by the concrete prism test)(Table 2). Previous studies had indicated that 35% slag (from the same source as tested in this study) was sometimes sufficient [8] or insufficient [10] to reduce Sudbury expansions to less than 0.10% at 14 days. Both 30% and 35% fly ash produced acceptable results. Thus, as intended, for these aggregates, the mortar bar test results are generally more conservative than the concrete prism results.

As shown in Table 4, for both Spratt and Sudbury aggregate mixtures with alkalies increased to 1.25% of cement as per the 2004 version of the CSA A23.2-28A standard (the A condition), the concrete prism test and the mortar bar test agree 2 times out of 3, with the concrete prism test showing a pass for the lower value of slag cement replacement (50% with Spratt and 35% with Sudbury), while the mortar bar test fails that same combination. For the B condition, the two tests agree 4 out of 5 times, again with the discrepancy occurring at the lower level of slag cement replacement, where the combination passes the concrete prism test but fails the mortar bar test. The concrete prism test results suggest that the levels of SCM replacement prescribed in the current CSA A23.2-27A standard are sufficient when using cements with alkali contents up to approximately 1.15%. All concrete mixtures tested at both the 1.25% alkali (A) and 0.25% additional alkali (B) conditions passed using slag cement and fly ash, although mixes incorporating 35% slag and the 1.11% cement with the Sudbury aggregate induced concrete prism expansions close to the 0.040% expansion level (0.036 and 0.037%), as mentioned before. For the highly reactive Spratt aggregate, the levels outlined in the Table 6 of CSA A23.2-27A are 50% slag cement or 35% fly ash (Type CI with 3.0-4.5% alkali). For the moderately reactive Sudbury aggregate, the levels are 35% slag cement or 30% fly ash.

In the CSA standards, once concrete prism test data become available, those results govern over "interim" mortar bar data. The results obtained in the first part of the study (i.e. reported in Table 2) suggest that the SCM levels outlined in the Table 6 of CSA A23.2-27A to mitigate deleterious ASR expansions in concrete appear to be acceptable for cements with an alkali content up to about 1.15% (Na_2Oeq). The three high-alkali cements tested, including the two exceeding 1.00% (1.08 and 1.11%), all had 2-year concrete prism expansions below the CSA 0.040% limit when used with the appropriate levels of SCM replacement. Even mixtures with the highly reactive Spratt aggregate and 1.11% alkali cement produced expansions less than the CSA limit of 0.040% at 2 years when mitigated following CSA A23.2-27A.

For the companion test prisms cast as part of the outdoor exposure program (second part of the study), it is to be noted that only the 1.22% cement mix meets the requirement of CSA A23.2-28A, i.e. alkalies in the mix were boosted to 1.25% Na_2Oeq, by cement mass. The 2-year 38^{o}C prisms with Sudbury showed increasing expansion of the Portland cement mixtures (controls) with increasing alkali content. However, there was no corresponding trend with the Spratt aggregate (Table 5). For the Spratt Aggregate, by the 38^{o}C prism expansions, 35% slag was insufficient mitigation with the two highest alkali cements (1.10 and 1.22%) and 50% slag was found to be borderline, or just insufficient, with the 1.22% alkali cement (0.046% - Table 5). This suggests that higher levels of mitigation are needed for cements with alkali contents exceeding 1.10%; previous testing with Spratt aggregate has shown that 35% slag is borderline as in other studies it has been found to be insufficient [1, 2, 8], but 50% slag has consistently been sufficient [1, 2, 7, 8, 10]. Based on the 38^{o}C prism expansions with Sudbury aggregate, 30% slag was insufficient mitigation with the two highest alkali cements (1.10 and 1.22%), and 40% slag was insufficient with the 1.22% alkali cement (also boosted to 1.25% with NaOH) (Table 5). CSA A23.2-27A would typically require 35% slag to mitigate the Sudbury aggregate, so it appears that a higher level of mitigation is required with cements with higher than approximately 1.1% alkali content.

As shown in Figure 1, after 2 years at 38^{o}C, little expansion occurred with Spratt aggregate mixtures, but with Sudbury aggregate, expansion is continuing at a fairly constant rate after 4 years. So either any alkali leaching from the prisms in the containers is insufficient to slow the rate of expansion or possibly this aggregate is releasing alkalies to sustain expansion. Previously, the Sudbury aggregate has been found to release alkalies in hot water extraction tests [9]. Further experiments are in progress to determine if alkalies are being released by the constituents of the Sudbury aggregate. Another possible process/explanation is that some of the alkalies added to the mix water as NaOH become bound during cement hydration, whereas more of the cement alkalies may become available later during ASR reactions. On the other hand, faster expansions and associated cracking developing in concrete prisms incorporating highly-reactive aggregates (such as Spratt) would likely promote alkali leaching and reduction in later expansion rates (Figure 1).

For the 60^{o}C prisms expansions at 6 months, with both reactive aggregates, expansions increased with cement alkali content for the 100% cement mixtures. As well, with Spratt, 35% slag was insufficient for the two highest alkali cements (1.10 and 1.22%). With the Sudbury aggregate, 30% slag was insufficient for the 1.22% cement, but 40% was acceptable; CSA A23.2-27A would require 35% slag for a 75-year service life in a moist environment. It is interesting that the 60°C concrete prism test after 6 months is less conservative than the 2-year 38°C concrete prism test in terms of obtaining expansions greater than 0.040%. This may be due to higher rates of alkali leaching in the 60°C test.

Although, for both the Spratt and Sudbury aggregates, the expansion of the 100% cement (i.e. control) outdoor concrete blocks was found to increase with increasing cement alkali content, only those made with the Spratt aggregate have expanded significantly after 4 years. None of the SCM mitigated mixes with either aggregate are expanding (Table 7); however, it is likely, based on previous outdoor exposure studies [6, 7, 10], and on the data in Table 9 (B. Fournier, personal communication from same study as [6]), that a minimum of 10-12 years will be needed to prove adequacy of these mitigated mixtures with the exposure blocks. The results in Table 9 suggest that increasing the alkali content in concrete blocks (unboosted vs boosted blocks) may result in noticeable increase in expansion for concretes where the SCM content is "borderline", i.e. close to the minimum required to counteract expansion with that particular SCM.

5 CONCLUSIONS

This study was carried out in order to determine the safe alkali level in portland cement that could be used in concrete incorporating alkali-reactive aggregate together with the recommended SCM replacement levels in the Table 6 of CSA A23.2-27A. Based on the concrete prism test results obtained in both test programs, when using cements with alkali contents between 1.00% and about 1.10%, the levels of SCM replacement as prescribed in the Table 6 of CSA A23.2-27A for each required prevention level appear to be sufficient to mitigate deleterious expansions due to alkali-silica reaction (the above SCM replacement levels had originally been proposed for cements with alkali contents of ≤ 1.00% Na_2Oeq). These results support the changes made in the 2009 revision to the CSA standards that now allow the use of cements with alkali contents up to 1.15% Na_2O_{eq} in CSA A23.2-27A with the current levels of SCM mitigation for moderately reactive aggregates (aggregates with 1-year 38°C concrete prism expansions up to 0.120%). More highly reactive aggregates can now be used with cements having alkali contents between 1.00 and 1.25% Na_2O_{eq} provided that the level of mitigation using SCMs is raised by one level. As well, using the "performance testing" approach, CSA A23.2-28A was amended to allow testing of SCMs together with cements having alkali contents greater than 1.00%, provided its alkali content is raised by an additional 0.25% in the concrete mixture, as was done in Series B in this work.

Six month expansions in the RILEM AAR-4 60°C concrete prism test do not appear to be conservative relative to 2-year 38°C expansions. More time is needed for the outdoor exposure blocks to yield useful data and to further evaluate the reliability of the data obtained from the laboratory investigations.

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Table 1: Compositions of Cementing Materials: lab test data on left, exposure block data on right

	Laboratory testing program					Field exposure test program				
	Cements			Fly Ash	Slag Cement	Cements			Fly Ash	Slag Cement
	0.97% alkali	1.08% alkali	1.11% alkali			0.96% alkali	1.10% alkali	1.22% alkali		
SiO_2, %	18.95	19.17	19.44	55.03	34.95	18.90	19.54	20.40	53.90	34.95
Al_2O_3, %	5.77	5.02	4.46	23.20	10.71	4.58	5.12	4.30	23.40	10.00
Fe_2O_3, %	2.58	2.60	3.24	3.66	0.51	3.03	2.63	2.80	4.42	1.05
CaO, %	63.15	62.21	60.48	10.57	35.88	61.10	61.85	61.70	11.00	38.20
MgO, %	2.22	2.50	4.08	1.18	11.68	2.38	2.49	3.40	1.13	11.20
Na_2O, %	0.31	0.34	0.13	3.07	0.36	0.34	0.34	0.44	3.29	0.52
K_2O, %	1.00	1.12	1.49	0.70	0.52	0.94	1.15	1.19	0.81	0.60
Na_2Oeq, %	0.97	1.08	1.11	3.53	0.70	0.96	1.10	1.22	3.82	0.91
SO_3, %	4.36	4.09	4.51	0.19	1.35 S-	4.23	3.78	3.70	0.16	1.53 S-
LOI, %	1.66	—	—	0.40	—	2.74	3.04	1.58	0.64	—
C_3S, %	57.2	57.0	51.0	—	—	—	54.0	52.0	—	—
C_2S, %	10.2	11.0	17.3	—	—	—	15.0	19.0	—	—
C_3A, %	10.7	9.0	6.3	—	—	9.2	9.1	7.0	—	—
C_4AF, %	7.7	8.0	9.8	—	—	—	8.0		—	—
Blaine m^2/kg	—	419	—	—	448	—	411	378	—	—

Table 2: 2-Year 38^{o}C Laboratory Concrete Prism Expansions

(Expansions > 0.040% in bold)

Series A: Cement alkali adjusted to 1.25%			
Spratt Aggregate	0.97% alkali	1.08% alkali	1.11% alkali
100% portland cement	**0.211%**	**0.218%**	**0.239%**
50% slag	0.012%	0.008%	0.020%
35% CI fly ash	0.009%	0.010%	0.019%
Series B: Cement alkali (A) increased by 0.25%			
		1.33%	1.36%
100% portland cement		**0.208%**	**0.256%**
50% slag		0.014%	0.018%
60% slag		0.008%	0.009%
35% CI fly ash		0.009%	0.013%
40% CI fly ash		0.008%	0.012%

Series A: Cement alkali adjusted to 1.25%			
Sudbury Aggregate	0.97% alkali	1.08% alkali	1.11% alkali
100% portland cement	**0.230%**	**0.231%**	**0.332%**
35% slag	0.029%	0.025%	0.037%
30% CI fly ash	0.016%	0.011%	0.020%
Series B: Cement alkali (A) increased by 0.25%			
		1.33%	1.36%
100% portland cement		**0.223%**	**0.301%**
35% slag		0.032%	0.036%
50% slag		0.000%	0.012%
30% CI fly ash		0.006%	0.006%
35% CI fly ash		0.006%	0.005%

Table 3: Accelerated Mortar Bar Expansions at 14 Days

(Expansions > 0.100% in bold)

	Spratt Aggregate	Sudbury Aggregate
100% cement	**0.444%**	**0.362%**
60% slag	0.047%	
55% slag	0.062%	
50% slag	**0.147%**	0.042%
45% slag		0.095%
40% slag		**0.109%**
35% slag		**0.155%**
40% fly ash	0.046%	
35% fly ash	0.036%	0.025%
30% fly ash		0.042%

Table 4: Comparison of 2-Year 38^{o}C Concrete Prism and 14-Day Accelerated Mortar Bar Results

	Spratt Aggregate			Sudbury Aggregate		
	C1293 Series A	C1293 Series B	C1567	C1293 Series A	C1293 Series B	C1567
100% cement	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
60% slag	—	PASS	PASS			
50% slag	PASS	PASS	FAIL	—	PASS	PASS
35% slag				PASS	PASS	FAIL
40% fly ash	—	PASS	PASS			
35% fly ash	PASS	PASS	PASS	—	PASS	PASS
30% fly ash				PASS	PASS	PASS

Table 5: 2-Year 38^{o}C Concrete Prism Expansions from Block Program Mixtures

(Expansions > 0.040% in bold)

Spratt Aggregate	0.96% Cement	1.10% Cement	1.22%* Cement	**Sudbury Aggregate**	0.96% Cement	1.10% Cement	1.22%* Cement
100% Cement	**0.402**	**0.406**	**0.359**	100% Cement	**0.201**	**0.317**	**0.360**
30% fly ash		0.016	0.019	25% fly ash		0.004	0.012
35% fly ash		0.008	0.007	30% fly ash		-0.004	0.002
40% fly ash		0.003	0.006	35% fly ash		-0.007	0.001
35% slag		**0.063**	**0.100**	30% slag		**0.055**	**0.112**
50% slag		0.027	**0.046**	40% slag		0.014	**0.050**
				50% slag		0.010	0.029

* NaOH added to obtain 1.25% alkali equivalent

Table 6: 6 Month 60 ^{o}C Concrete Expansions from Block Program Mixtures

(Expansions > 0.040% in bold)

Spratt Aggregate	0.96% Cement	1.10% Cement	1.22%* Cement	**Sudbury Aggregate**	0.96% Cement	1.10% Cement	1.22%* Cement
100% Cement	**0.139**	**0.196**	**0.195**	100% Cement	**0.087**	**0.162**	**0.304**
30% Fly Ash		0.011	0.018	25% Fly Ash		0.001	0.001
35% Fly Ash		0.006	0.006	30% Fly Ash		0.001	0.001
40% Fly Ash		0.009	0.002	35% Fly Ash		-0.002	0.001
35% Slag		**0.040**	**0.044**	30% Slag		0.014	**0.040**
50% Slag		0.019	0.010	40% Slag		0.001	0.018
				50% Slag		0.002	0.004

* NaOH added to obtain 1.25% alkali equivalent

Table 7: 4-Year Outdoor Exposure Concrete Block Expansions

(Expansions > 0.040% in bold)

Spratt Aggregate	0.96% Cement	1.10% Cement	1.22%* Cement	**Sudbury Aggregate**	0.96% Cement	1.10% Cement	1.22%* Cement
100% Cement	**0.061**	**0.074**	**0.075**	100% Cement	**0.010**	**0.016**	**0.017**
30% fly ash	-0.006	-0.004	-0.004	25% fly ash	-0.006	-0.003	-0.002
35% fly ash	-0.007	-0.006	-0.006	30% fly ash	-0.006	-0.004	-0.003
40% fly ash		-0.006	-0.004	35% fly ash		-0.005	-0.004
35% slag		0.006	0.013	30% slag		0.005	0.009
50% slag		0.003	0.001	40% slag		0.005	0.009
				50% slag		0.004	0.009

* NaOH added to obtain 1.25% alkali equivalent

Table 8: Compositions of Cementing Materials: Exposure Blocks from the CANMET study [10]

	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	Na_2Oeq (%)	SO_3 (%)	LOI (%)	Blaine (m^2/kg)
Cement	20.15	5.52	2.59	61.72	2.19	0.18	1.09	0.90	4.98	1.54	399
Fly ash	50.16	26.84	12.75	2.39	0.89	0.26	2.24	1.73	0.78	2.80	273
Slag	35.70	9.60	0.55	34.30	14.10	0.53	0.42	0.81	3.69	1.59	436

Table 9: 4 and 12-year Expansions of Similar Exposure Blocks incorporating the Spratt and the Sudbury Aggregates (Expansions > 0.040% in bold)

Cementitious materials	**Spratt Aggregate**				**Sudbury Aggregate**			
	Unboosted blocks (0.90% Na_2Oeq Cement)		Boosted blocks (0.90% cement raised to 1.25% Na_2Oeq)		Unboosted blocks (0.90% Na_2Oeq Cement)		Boosted blocks (0.90% cement raised to 1.25% Na_2Oeq)	
	4 Years	12 Years	4 Years	12 Years	4 Years	12 Years	4 Years	12 Years
100% Cement	**0.055**	**0.185**	**0.069**	**0.244**	0.006	**0.166**	0.008	**0.145**
30% Fly Ash	0.007	0.014	0.009	0.029	0.001	0.008	0.000	0.011
35% Slag	0.008	**0.046**	---	---	0.007	0.028	0.006	0.038
50% Slag	0.006	0.015	0.007	0.026	0.013	0.025	0.006	0.023

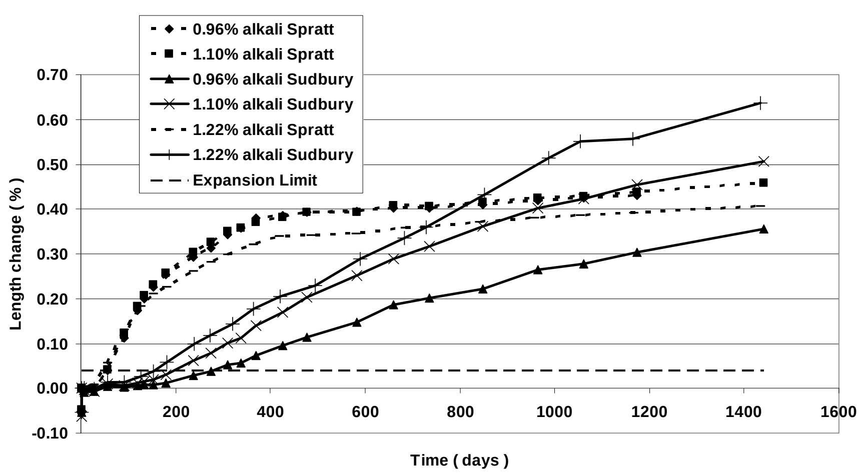

Figure 1: 38°C Concrete Prism Expansions up to 4 Years from Exposure Block Program (100% Cement mixtures)