COMPARATIVE FIELD AND LABORATORY INVESTIGATIONS ON THE USE OF SUPPLEMENTARY CEMENTING MATERIALS (SCMs) TO CONTROL ALKALI-SILICA REACTION (ASR) IN CONCRETE

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ABSTRACT

A comparative field and laboratory research program was initiated at CANMET in 1991 for evaluating the efficacy of laboratory tests for reliably evaluating the potential alkali-reactivity of concrete aggregates and the efficacy of SCMs in preventing ASR. Air-entrained concrete mixtures were made with a variety of reactive aggregates and SCMs, from which test prisms and exposure blocks were cast. The various combinations were also tested in the Accelerated Mortar Bar Test. The concrete prism and accelerated mortar bar tests were effective in predicting the potential alkali-reactivity of the aggregates selected. Concrete prism testing in accordance with CSA A23.2-28A reliably predicts the efficacy of SCMs for preventing short term exposure block expansions (~10 year); however, the correlation is decreasing afterwards. Extending the testing period in the "control" laboratory condition or exposing concrete prisms to a source of external alkalis can sometimes improve correlations, but the beneficial effect varies from one aggregate and one SCM to another.

Key words: Alkali-silica reaction, supplementary cementing materials, concrete prism test, accelerated mortar bar test, field exposure.

1 INTRODUCTION

Over the past few decades, recommended practices/guidelines were proposed for selecting preventive measures against ASR in concrete. These generally include a *performance* approach based on laboratory testing, and a *prescriptive* approach following a risk analysis based on the determination of the reactivity level of the aggregate, the type, size and exposure conditions of the structure, and the composition of cementitious materials proposed for use (e.g. [1-6]). Thomas et al. [7,8] presented a critical review of the use of the accelerated mortar bar test (AMBT; [3,9]) and the concrete prism test (CPT; [3,10]) for evaluating the effectiveness of SCMs for controlling ASR. Several comparative field and laboratory investigations were developed for validating the results obtained with the above tests (e.g. [11-17]). This paper compares the most recent data obtained from a research program initiated in the early 1990's at CANMET, a division of the Department of Natural Resources Canada [18,19].

2 OBJECTIVES AND SCOPE OF THE PROGRAM

The main objective of the CANMET study was to contribute at providing the Industry with quick and reliable testing methods for evaluating the potential alkali-reactivity of concrete aggregates, as well as the long-term effectiveness of SCMs and lithium-based products in controlling expansion due to ASR. A testing matrix was developed including reactive aggregates and cementitious materials from different parts of the world. From each of the mixtures made in this study, concrete prisms and exposure blocks were cast and subjected to accelerated test conditions in the laboratory or to natural environmental conditions at CANMET outdoor exposure site (Ottawa, Canada). Expansion and cracking due to ASR were (laboratory testing) and are still (exposure blocks) being monitored. Most combinations were also tested in the AMBT [3,9].

3 MATERIALS USED

Table 1 gives the petrographic description and the physical properties of the fine and coarse aggregates used in this study. The chemical composition of the five low- and high-alkali portland cements (C), six low-calcium fly ashes (FA), two ground granulated blast furnace slags (Sg), and the high SiO_2 silica fume (SF) used in this study is given in the Table 2. For practical reasons and whenever possible, reactive aggregates were tested with cements and SCMs from the same geographical region; the cementitious materials used in combination with the aggregates selected (in concrete and mortar mixtures) are given in Table 1.

A synthetic resin type air-entraining admixture was used in all concrete mixtures, from which laboratory specimens and exposure blocks were cast. Reagent grade NaOH pellets were used to increase the

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alkali content in a number of concrete mixtures to selected levels. A commercially available sulphonated, naphthalene formaldehyde condensate superplasticizer was used in the silica fume mixtures, as well as for high-volume fly ash concrete (HVFAC) mixtures (i.e. 56% fly ash content).

4 MIXTURE PROPORTIONING

4.1 Concrete mixtures

Air-entrained concrete mixtures were made with nominal cementitious materials content of 420 ± 10 kg/m^3, except for the high-volume fly ash mixtures for which 375 ± 10 kg/m^3 was selected. Control concretes were made with low-alkali (LA) and high-alkali (HA) cements only. The SCMs were used as replacement, by mass, of the <u>high alkali cement</u>, i.e. 20, 30 and 56% for fly ash, 35, 50 and 65% for slag and 7.5, 10 and 12.5% for silica fume.

A fixed coarse-to-fine aggregate ratio of 60:40, by mass, was used in all mixtures. The water-to-cementitious material ratio was adjusted as follows: 0.40 to 0.42 (0.37 to 0.39 for gravel aggregates Al and Ed) for control concretes; 0.38 to 0.41 (0.34 to 0.36 for gravel aggregates Al and Ed) for the fly ash (FA) mixtures; 0.32 for high-volume fly ash concretes (56% fly ash); 0.40 - 0.41 for slag concretes; 0.41 - 0.42 for SF concrete mixtures, with superplasticizer to provide proper dispersion of the SF.

Most control and SCMs concrete mixtures were made with and without added alkalis. For the "boosted alkali mixtures", reagent grade NaOH pellets were dissolved in the mixing water in order to increase the total alkali content corresponding to the <u>cement</u> part of the concrete system to 1.25% Na_2O equivalent.

4.2 Mortar mixtures

The combinations (control and SCMs replacement levels) tested in concrete were also reproduced in mortars using the recommendations of CSA A23.2-28A, i.e. 990g of graded aggregates, 440g of cementitious materials and a fixed water-to-cementitious materials ratio of 0.50. The SCMs were used as replacement, by mass, of the HA cement. All mixtures were made without superplasticizer and without added alkalis.

5. MANUFACTURING AND TESTING OF SPECIMENS

5.1 Concrete mixtures

All concrete mixtures were made in a large laboratory pan mixer (0.40 m^3 capacity). Twelve test prisms, 75 by 75 by 300 mm in size, and two blocks, 0.40 by 0.40 by 0.70 m in size, were cast from each of the above mixtures. The concrete prisms were stored in the following conditions, by sets of three: (A) 38°C and RH > 95%, (B) 1N NaOH at 38°C, (C) 1N NaOH at 80°C and (D) 5% NaCl. Length change measurements were performed at regular intervals over 4-year (condition A), 3-year (conditions B and D) and one-year (condition C) periods. Results of concrete prism expansion testing in storage condition D are not reported in this paper as very limited expansions were obtained for prisms maintained under that condition.

Eight stainless steel threaded studs, 9 mm (diameter) by 75 mm (length), were partially embedded in the sides and on the top of the concrete blocks for length-change monitoring. The blocks were placed on the outdoor exposure site, which consisted of well-compacted layer of 0-19-mm (gravel A) crushed limestone material (Figure 1). One block of each set was placed directly on the compacted gravel while the second block was placed above ground, sitting on two 200 mm in diameter by 0.40 m long concrete cylinders cut lengthwise. Length-change measurements are being taken on the longitudinal axis on the top and sides of the blocks, generally once a year under similar conditions (cloudy day; temperature of 23±2°C). Crack width measurements are also taken on the blocks during the same field operations.

5.2 Mortar specimens for laboratory testing

According to [3], three mortar bars, 25 by 25 by 225-mm in size, were cast from each of the various mortar mixtures made in this study. After the 24-hour precuring period in tap water at 80 ± 2°C, the mortar bars were measured and transferred in plastic storage containers filled with a 1N NaOH solution at 80°C; their length change in the 1N NaOH solution at 80°C was monitored regularly over a 28-day testing period.

6 RESULTS OF LABORATORY AND FIELD TESTING

A full description of the test results cannot be presented here due to space limitations. The following sections focus on the main correlations extracted from the analysis of the data produced so far in this study.

6.1 Evaluation of the potential alkali-reactivity of concrete aggregates

The alkali-reactive character of all aggregates was well recognized through the expansion testing both in the laboratory and in the field. Figure 2A and 2B indicates that concrete prism/block and mortar bar expansions well in excess of the respective "acceptance" limits were observed for all high-alkali control systems tested (i.e. CPT condition A and AMBT). There are currently no expansion limits available for CPT storage conditions B and C; however, the expansion values after 52 weeks and 8 weeks in the above conditions, respectively, were found to correlate well with those obtained for exposure blocks.

6.2 Evaluating the effectiveness of low-alkali cement and SCMs for controlling ASR expansion

Low alkali cements

Figure 2C shows that the use of low-alkali cements was effective in controlling ASR expansion up to 15 years with 7 out of the 10 aggregates investigated. Interestingly, the exposure blocks incorporating the very-low alkali cement C2 are still experiencing slight shrinkage after 15 years outdoors.

Fly ash concretes

For the marginally/moderately-reactive aggregates Su, Al, Gr and Ed, the use of 20% (and 30%) of the low-calcium fly ashes used in this study, as replacement by mass of the high-alkali cement, contributed at keeping exposure block expansions below or very close to the 0.050% expansion level after 15 years of field exposure (Figure 3). In the case of the highly-reactive aggregates Sp, Sl, Con and NM, using 20% fly ash resulted in significant expansion reductions compared to the high-alkali controls; however, such a replacement level was ultimately insufficient for controlling exposure block expansion to an acceptable level after 10 or 15 years. Replacing the high-alkali cement by 30% fly ash kept exposure block expansions to < 0.050% for the aggregates Sl and Con at 10 years but not at 15 years, while it could not adequately control the expansion of the exposure block incorporating the extremely-reactive NM aggregate at both time periods (Figure 3). None of the blocks incorporating 56% fly ash expanded significantly at 15 years of field exposure.

Figures 4A and 4B compare the "expansion-at-selected-time-limits" for laboratory and field specimens cast from fly ash concrete and mortar mixtures. The selected testing periods for the storage condition A (CPT, 104 weeks) and for the AMBT (14 days) correspond to those recommended by CSA Standard Practice A23.2-28A [3], while those proposed for CPT conditions B (52 weeks) and C (8 weeks) were found appropriate in the case of control mixtures (Figure 2B). Despite a few exceptions, somewhat satisfactory correlations can be observed between laboratory test results at the above time periods and 10-year exposure block expansions (Figure 4A); however, the number of false negative results increases significantly when the above laboratory testing periods are compared to 15-year exposure block expansions (lower right portion of Figure 4B). Increasing the testing period in the various laboratory test conditions helps at reducing the number of "anomalies" (lower right part of Figure 4C); however, this also increases the number of false positive results (upper left part of Figure 4C).

Silica fume and slag concretes

For the moderately-reactive aggregates Su, Al and Lm, 7.5 to 12.5% silica fume contributed at keeping exposure block expansions to < 0.050% at 10 years, even at 15 years for the Su and Al aggregates (Figure 5). Replacing the high-alkali cement by minimum 7.5% silica fume was also effective in reducing the expansion of exposure blocks incorporating the highly-reactive aggregates Sp, Po and Sl under 0.050% at 10 years; however, a 10% replacement level was barely sufficient to keep the expansion under the above expansion level at 15 years for the aggregates Sp and Sl (Figure 5).

For the moderately-reactive aggregate Su, the use of 35 to 65% ground granulated blastfurnace slag contributed at keeping expansions in unboosted exposure blocks to < 0.050% at 15 years (Figure 6). In the case of the highly-reactive aggregate Sp, 35% slag was found insufficient in reducing exposure block expansion < 0.050% at 15 years (Figure 6). None of the blocks incorporating 65% slag and the various aggregates investigated (Su, Sl, RG, Ql and Re) expanded significantly even at 15 years of field exposure.

Figures 4D and 4E compare the "expansion-at-selected-time-limits" for laboratory and field specimens cast from silica fume or slag concrete and mortar mixtures. Once again, the selected testing periods for condition A (CPT, 104 weeks) and for the AMBT (14 days) correspond to those recommended by CSA Standard Practice A23.2-28A [3], while those proposed for CPT conditions B (52 weeks) and C (8 weeks) were used for control mixtures (Figure 2B). When correlating lab data with the 10-year exposure block expansions, false positive results were obtained for several SF mortar (AMBT) and concrete specimens (upper left portion of Figure 4D). The number of "anomalies" increases significantly when the above laboratory testing periods are compared to 15-year exposure block expansions (lower right portion of Figure 4E). The testing period in the various laboratory test conditions can be increased for minimizing the number of such "anomalies"; however, this results in a large number of false positive results (upper left part of Figure 4F).

7 DISCUSSION

The correlations illustrated in Figure 4 are for laboratory test prisms and exposure blocks cast from concrete mixtures with and without added alkalis, respectively. The above data show a progressive loss of correlation between the concrete prism expansions obtained under the "standard" condition A, i.e. after 104 weeks at 38°C and R.H. > 95%, and the 15-year expansions in concrete blocks stored outdoors at the CANMET exposure site, likely partly due to the alkali leaching from the laboratory test prisms stored under the above conditions. However, the lower permeability characteristics of concretes incorporating SCMs likely keep the alkali leaching rate lower than that observed for control concretes as a slow and steadily increasing expansion trend in many concretes prisms incorporating reactive aggregates and "borderline amounts" of SCMs (in terms of reducing ASR expansion under an acceptable limit) is observed beyond the "typical" testing period, e.g. after 104-week as specified in CSA Standard Practice A23.2-28A (prisms stored at 38°C and R.H. > 95%). The testing period required under the above storage condition to "match" the results obtained in exposure blocks then becomes way too long (e.g. 208 weeks in Condition A – Figure 4C and 4F).

Providing a source of external alkalis and/or increasing the storage temperature could potentially offer a solution to compensate for alkali leaching in the "standard" condition A and/or improve correlations with exposure block expansions. Storing the concrete prisms in a 1N NaOH solution at 38°C resulted in higher expansions (compared to test prisms stored under condition A), but in some cases after only several months of testing (Figure 7). The lower permeability of SCMs concretes and the relatively low testing temperature (38°C) also seemed to limit, in many cases, the expansion rates or the magnitude of expansion of test prisms stored in the 1N NaOH solution at 38°C. This resulted in extended testing periods to match the results of exposure blocks (e.g. 156 weeks for fly ash concretes- Figure 4C; 104 weeks for silica fume and slag concretes – Figure 4F). The expansion of test prisms stored in the 1N NaOH solution at 80°C (condition C) develops much faster and continues at a fair rate as a function of the SCM types and contents; however, the high severity of the test conditions often results in false positive results (excessive expansion in the laboratory), while the effect varies from one type of SCM to another. Large expansions were indeed rapidly obtained for silica fume concretes compared to fly ash concretes for test specimens subjected to storage condition C, which may be partly related to the difference in the original alkali content (higher for SF concretes) of the concrete mixtures. For example, an interesting (but still imperfect) correlation is found between the 18-week expansion of FA test prisms stored in 1N NaOH solution at 80°C and the 15-year exposure block expansions (Figure 4C); however, even a 13-week testing period in storage condition C generates a significant number of false positive cases for SF concretes (upper left portion of Figure 4F).

The efficacy of storage conditions B and C for enhancing the correlation with exposure block expansions was found to vary from one aggregate to another and from one type of SCM to another. The beneficial effect of SCMs in controlling expansion due to ASR is indeed partly related to increased alkali binding capacity of the "pozzolanic CSH" [20], which contributes at reducing the pH of the pore solution under a threshold value necessary to generate expansion with each individual aggregate. Concretes incorporating SCMs are also significantly less permeable to the moisture ingress than conventional concrete. The use of the severe and somewhat "unrealistic" storage conditions B and C is not entirely satisfactory from a mechanistic point-of-view and are far from reproducing the real conditions to which concrete structures are subjected to. Moreover, the abundant alkali supply and higher testing temperature (especially at 80°C) could and likely will, amongst other things, generate deleterious/unexpected reactions and impact the composition of the pore solution and the expansive properties of the alkali-silica reaction products. However, the "race" for a performance test that will reliably "mimic" the field performance of concrete mix designs is still very much opened; it has been and is still one of the various objectives of the RILEM technical committees TC ACS-P (2007-2014) and TC 258-AAA (2014-2019), and of many other AAR technical committees worldwide. For instance, researchers in Japan propose to wrap concrete prisms in a cloth incorporating an alkaline solution that mimics the pore solution composition of the binder combination investigated in order to eliminate the deleterious effects of alkali leaching on expansion [21].

Increasing the alkali content in the concrete mixtures had a significant impact on the expansion of the control and SCM test prisms in the laboratory, and on the outdoor exposure blocks, for the moderately-and highly-reactive aggregates tested in this study (Figures 8 and 9). In a number of cases, the addition of NaOH resulted in expansions in excess of the 0.050% expansion level at 10 and/or 15 years, depending on the mix design tested (Figures 9 and 10). The impact was generally stronger for silica fume concretes (Figure 10); the effectiveness of silica fume in controlling expansion due to ASR is related to the total alkali content in the concrete mixture [22], which is taken into account in Canadian recommendations for preventing ASR [2].

One additional reason for the progressive discrepancy between field and laboratory expansion data mentioned above is likely related to the combined effect of ASR and local environmental conditions. For instance, at the CANMET outdoor exposure site in Ottawa, freezing and thawing cycles can significantly contribute to the deterioration of concrete suffering from internal expansion processes, such as ASR, thus exacerbating the development of internal and surface expansion/cracking. Specifications will eventually need to take into consideration the local environmental conditions regarding the amount of SCMs required to control ASR expansion, as a certain proportion of SCM may be efficient in a particular environment but insufficient in another one (e.g. Texas vs Ottawa), as reported in [12].

8 CONCLUSIONS

The main results of the comparative field and laboratory investigations carried out on selected aggregates and cementitious systems in this study can be summarized as follows:

- The standard Concrete Prism Test (38°C, RH > 95%) and Accelerated Mortar Bar Test (1N NaOH, 80°C) were found to reliably identify the potential alkali-reactivity of aggregates selected in this study.
- The efficacy of low-alkali cements in controlling expansion due to ASR varies from one aggregate to another and is not necessarily a long-term solution against ASR.
- For the performance evaluation of concrete incorporating fly ash, silica fume or slag, it was found that the correlation between CPT results carried out in accordance with Standard Practice A23.2-28A (i.e. test prisms stored at 38°C and relative humidity > 95%) and exposure block expansions progressively decreases with time, likely partly due leaching of alkalis over the duration of the test and local environmental conditions at the CANMET site. Correlations were found to improve, in some cases, by exposing the laboratory test prisms to an external source of alkalis and/or using higher storage temperatures. However, the beneficial effect of using such conditions is still opened to debate as it varies from one aggregate to another, one type of SCM to another, while not reproducing real conditions to which concrete structures are subjected to.
- Developing outdoor exposure sites and carrying out field performance surveys is necessary to validate the efficacy of performance laboratory test procedures used for selecting efficient long term preventive measures against ASR in concrete infrastructure under different environmental conditions.

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TABLE 1: Aggregates and SCM used in the study. The cementitious materials used in concrete and mortar mixtures incorporating the reactive aggregates selected are also given (see also Table 2).

Type	**ID**	**Nature** [1]	**Reactivity level** [2]	**Origin**	**Rock Type**	**Cement**		**SCM**
						LA	HA	
Coarse	Su	G	MR	Canada	Sandstone, quartzwacke, arkose, greywacke and argillite	C1	C3	FA2,Sg1
	Al	G	MR	Canada	Sandstone, greywacke, mudstone, volcanic	C1	C3	FA3
	Ed	G	MR	Canada	Sandstone, claystone, chert	--	C4	FA4
	Lm	Cr	MR	Canada	Argillaceous limestone	C1	C3	SF
	Gr	Cr	NR/MaR	Canada	Granite and granitic gneiss	C1	C4	FA1,SF
	RG	G	NR	Australia	Granitic	C2	C5	FA6
	Sp	Cr	HR	Canada	Siliceous limestone	C1	C3	FA2,Sg1
	Sl	Cr	ER	Canada	Greywacke / Argillite	C1	C3	FA1,SF
	Con	Cr	HR	Canada	Greywacke	--	C4	FA1
	Po	Cr	HR	Canada	Siliceous sandstone	C1	C3	FA1,SF
	NM	G	ER	USA	Mixed volcanic, quartzite, sandstone	--	C4	FA5
	Ql	Cr	HR	Australia	Greywacke	C2	C5	FA6,Sg2
	Re	Cr	ER	Australia	Mixed volcanics	C2	C5	FA6,Sg2
Sand	Control	Na	NR	Canada	Natural derived from granite	C1	C2-C6	All but FA4
	From Ed	Na	MR	Canada	Same sourse as Ed gravel	--	C4	FA4

[1] G: gravel; Cr: Crushed aggregate material; Na (for natural sand)

[2] NR: non reactive; MaR: marginally reactive; MR: moderately reactive; HR: highly reactive; ER: extremely reactive

TABLE 2: Chemical analysis of the cements and SCMs used in this study.

Chemical analysis (%)	Low-alkali Cement (LA)		High-alkali Cements (HA)			Silica Fume	Fly ash (FA)						Slag (Sg)	
	C1	C2	C3	C4	C5	SF	FA1	FA2	FA3	FA4	FA5	FA6	Sg1	Sg2
SiO_2	21.15	19.74	20.15	20.42	21.07	93.60	41.72	50.16	55.62	60.37	59.15	63.71	35.70	33.96
Al_2O_3	4.00	4.56	5.52	5.08	4.60	0.06	19.70	26.84	20.33	20.98	19.13	24.28	9.60	12.62
Fe_2O_3	5.39	3.45	2.59	2.37	4.00	0.45	26.03	12.75	4.08	4.28	5.27	3.91	0.55	0.20
CaO	60.35	64.79	61.72	62.39	63.10	0.50	2.06	2.39	9.07	6.80	7.45	1.47	34.3	40.55
MgO	3.44	0.91	2.19	2.55	1.50	0.67	0.87	0.89	0.04	n.a.	2.47	0.57	14.1	6.38
SO_3	2.46	2.45	4.98	3.11	2.76	0.32	1.08	0.78	3.43	0.21	0.18	0.13	3.69	3.62
LOI	2.25	3.17	1.54	2.50	1.31	2.26	3.38	2.80	0.50	0.41	0.18	1.76	1.59	1.00
Na_2O	0.13	0.14	0.18	0.22	0.55	0.16	0.79	0.26	4.22	0.71	2.50	0.56	0.53	0.32
K_2O	0.41	0.16	1.09	1.03	0.48	0.85	2.12	2.24	1.85	0.43	1.06	1.65	0.42	0.29
Na_2Oeq	0.40	0.25	0.90	0.90	0.87	0.72	2.18	1.73	5.44	0.99	3.20	1.65	0.81	0.51

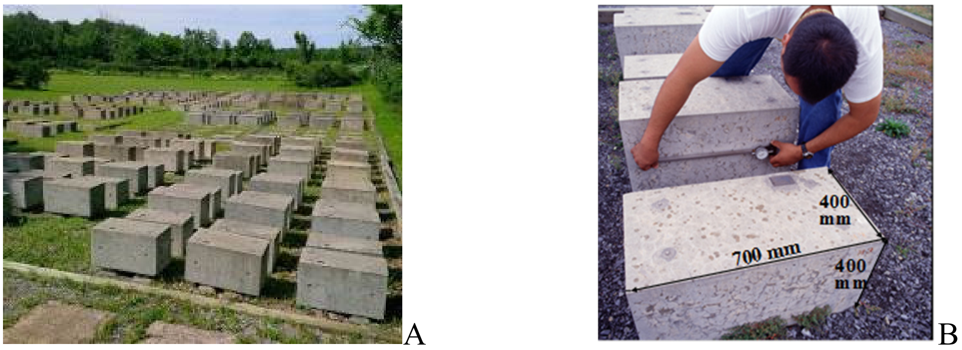
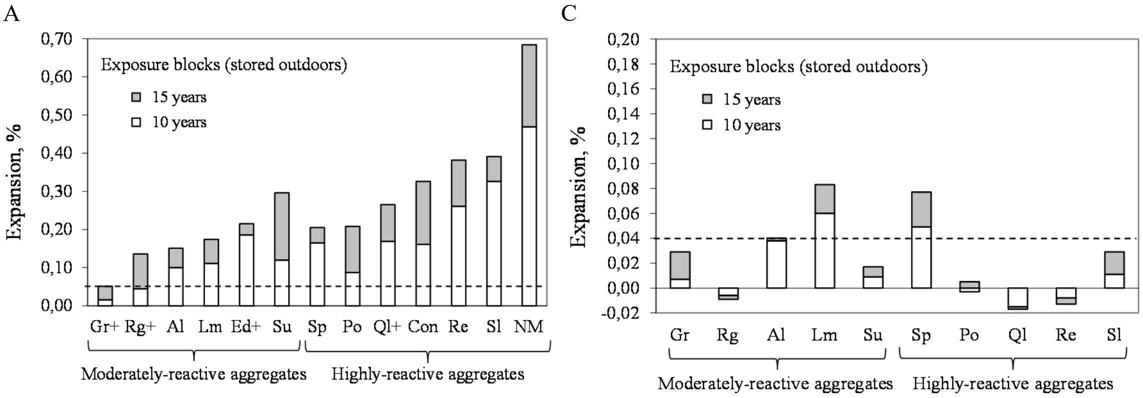


Figure 1: A. CANMET outdoor exposure site. B. Measurements of the exposure blocks.



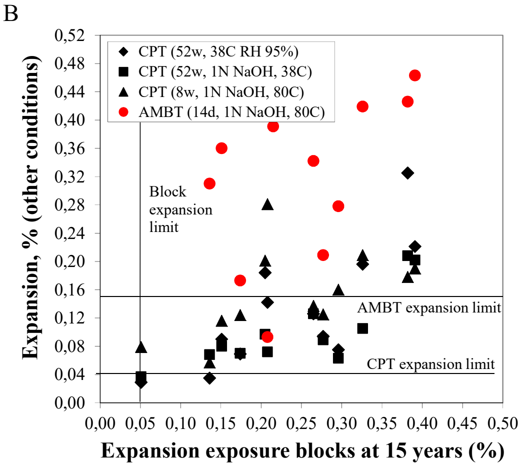


Figure 2: Expansion at different time periods for control concrete prisms/blocks and mortar bars made with high or low-alkali cement. A. 10 and 15-year expansions of control exposure blocks made with high-alkali cements (mixtures without added alkalis, except for the specimens Gr+, Rg+ and Ql+). B. Expansion at different time periods for control concrete prisms and mortar bars plotted against the 15-year expansions of exposure blocks. The data are reported for laboratory concrete specimens cast from mixtures with added alkalis, mortar specimens without added alkalis, and exposure blocks without added alkalis. C. 10 and 15-year expansions of control exposure blocks made with low-alkali cements.

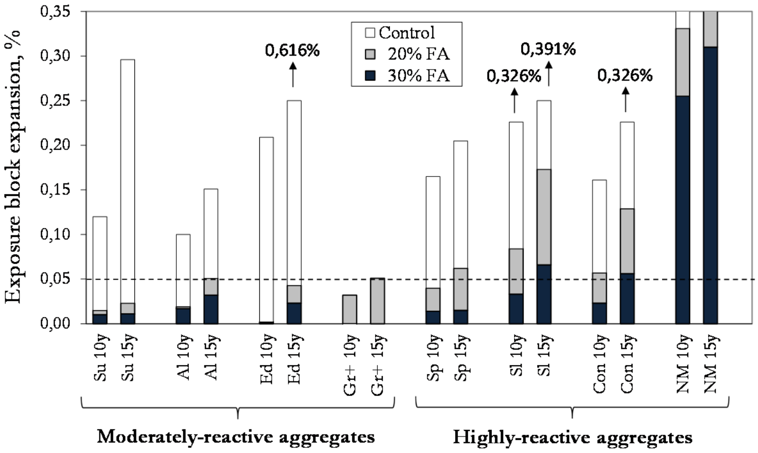
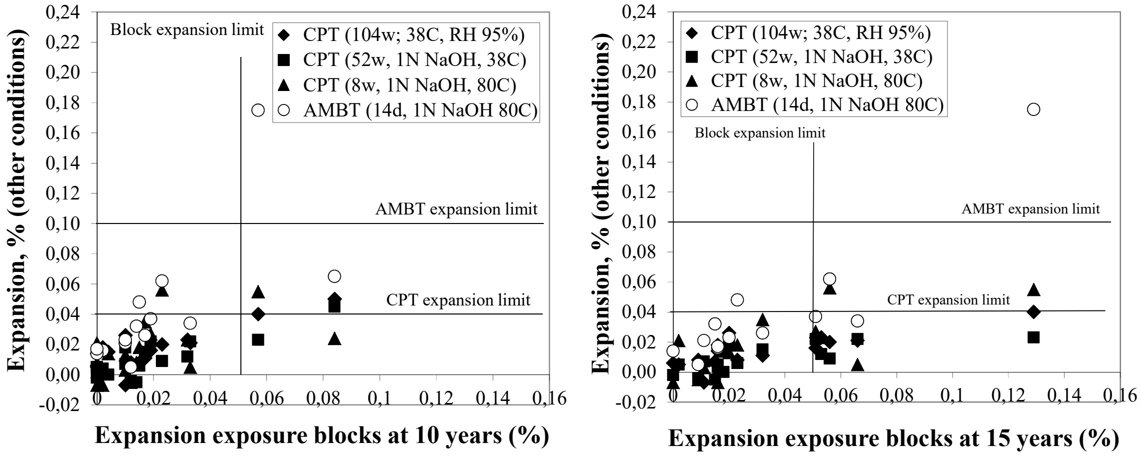


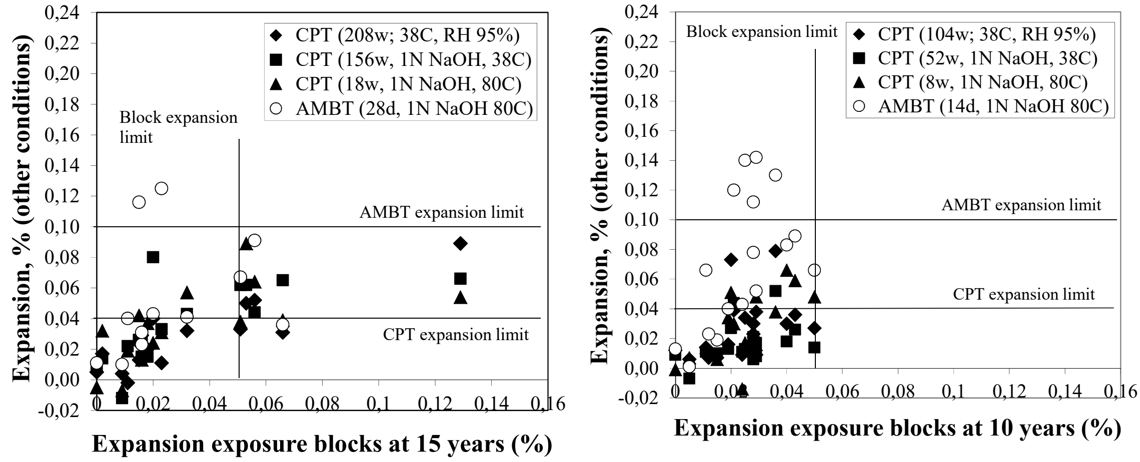
Figure 3: 10- and 15-year expansions of control and fly ash concrete exposure blocks. The data are presented for mixtures without added alkalis, with the exception of the blocks incorporating the Gr aggregate (Gr+; control at 10 years and 15 years: 0,015% and 0,051%). The 10- and 15-year expansions for the control blocks NM are 0.469% and 0.684%, respectively. The alkali content (in kg/m³, Na_2Oeq) of the concrete mixtures is as follows:

	FA content	0%	20%	30%
Alkali content	Control	3.78	--	--
	FA	--	3.02	2.65
	FA+	--	4.20	3.68

A – Fly ash mixtures B – Fly ash mixtures



C – Fly ash mixtures D – silica fume and slag mixtures



E - silica fume and slag mixtures F - silica fume and slag mixtures

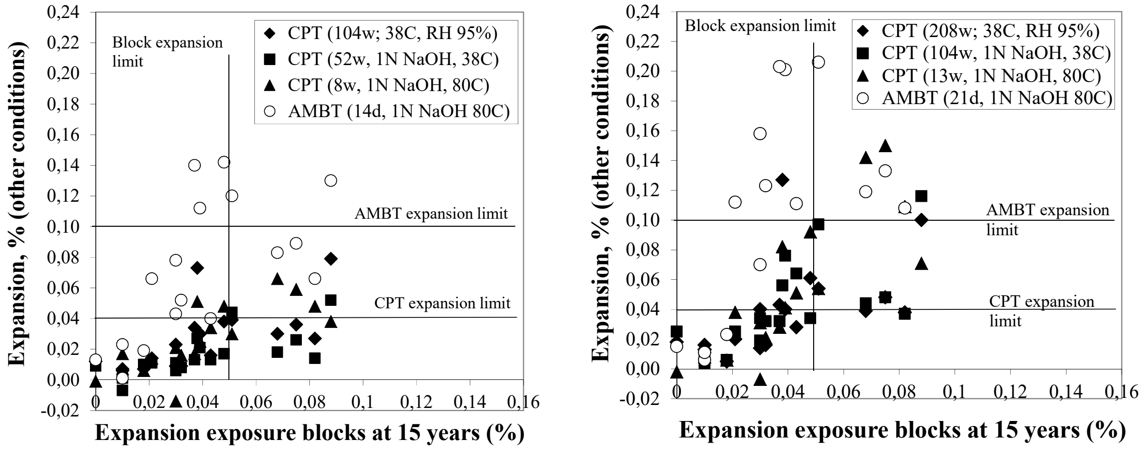


Figure 4: Expansion at different time periods for laboratory specimens plotted against the 10-year (A & D) and the 15-year (B,C,E,F) exposure blocks expansions. A to C: Fly ash mixtures. D to F: silica fume and slag mixtures. The data are reported for laboratory concrete specimens cast from mixtures with added alkalis, mortar specimens without alkalis, and exposure blocks without added alkalis. In the case of the Figures C & F, the testing period in the various laboratory conditions has been extended to seek for improved correlations.

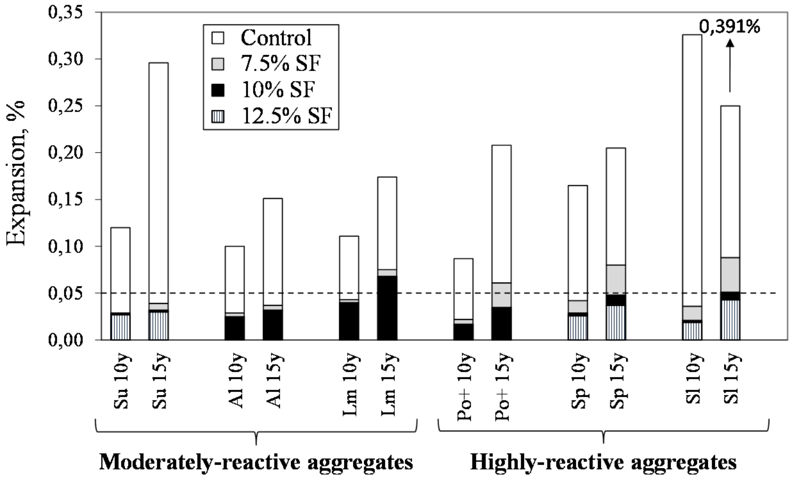


Figure 5: 10-year and 15-year expansions of control and silica fume exposure blocks. The data are presented for concrete mixtures without added alkalis. The alkali content (in kg/m^3, Na_2Oeq) of the concrete mixtures is as follows:

SF content	0%	7.5%	10%	12.5%
Alkali content	3.78	3.50	3.40	3.31

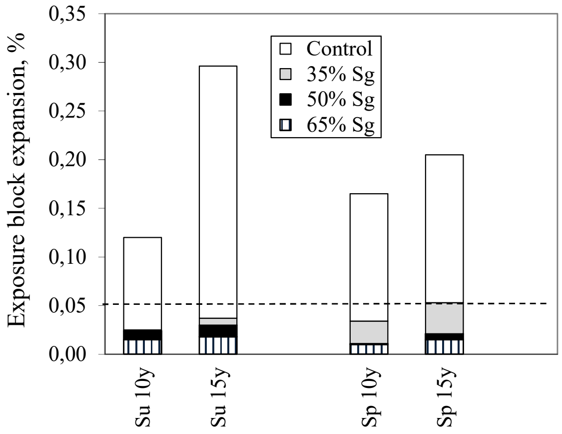


Figure 6: 10-year and 15-year expansions of control and ground granulated blastfurnace slag exposure blocks. The data are presented for concrete mixtures without added alkalis. The alkali content (in kg/m^3, Na_2Oeq) of the concrete mixtures is as follows:

Sg content	0%	35%	50%	65%
Alkali content	3.78	2.46	1.89	1.32

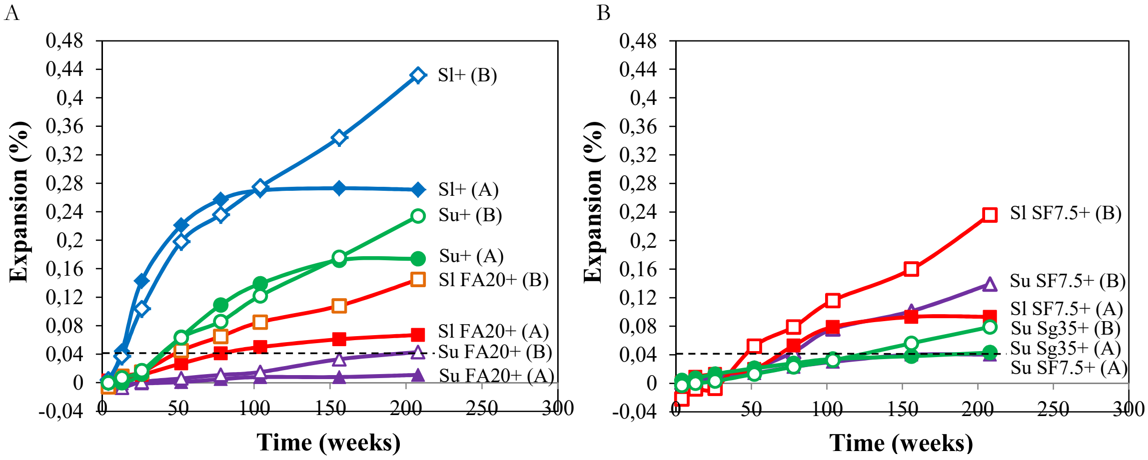


Figure 7: Concrete prism expansion test results for companion sets of test prisms incorporating the Sl (highly reactive) and Su (moderately reactive) aggregates and stored at 38^{o}C, R.H. > 95% (condition A) and 1N NaOH solution at 38^{o}C (condition B). In all concrete mixtures, NaOH was added to the mix water in order to increase the alkali content corresponding to the cement part of the mix to 1.25% Na_2Oeq (i.e. Sl**+**, Sl FA20**+,** etc.). A. Test prisms cast from control (high-alkali cement only) and 20% fly ash concrete mixtures. B. Test prisms cast from 7.5% silica fume and 35% slag concrete mixtures.

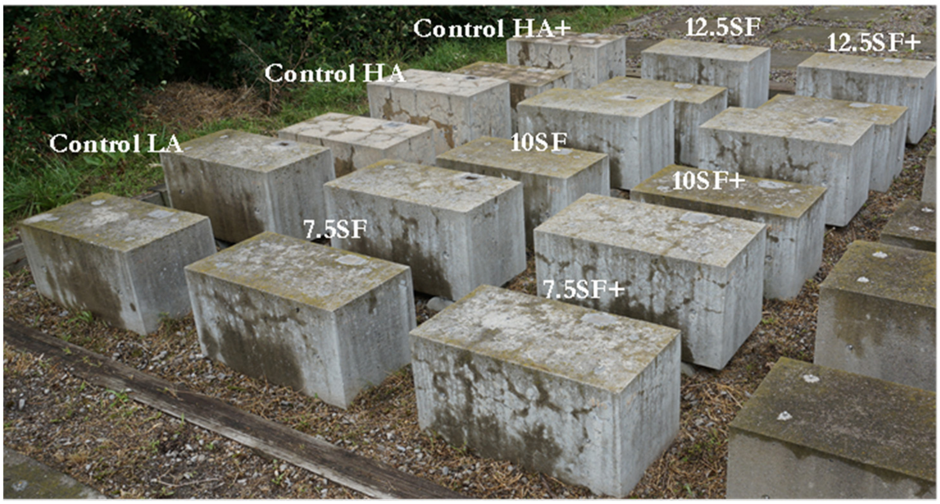


Figure 8: Exposure blocks incorporating the moderately-reactive Su aggregate. Each mix is represented by two blocks, one sitting directly on the ground and the second one sitting on small concrete supports so the block stands above ground. The mixtures correspond to low-alkali and high-alkali (unboosted and boosted) controls, and unboosted and boosted ("+ series") specimens incorporating 7.5, 10% and 12.5 silica fume. The alkali content of the silica fume concrete mixtures can be found in the legend of Figure 10).

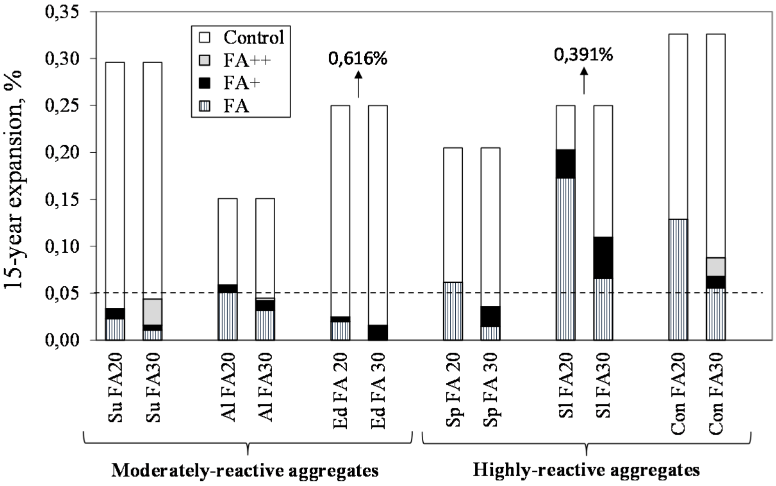


Figure 9: Effect of alkali addition on the 15-year expansion of fly ash exposure blocks. The alkali content corresponding to the <u>cement</u> part in the FA+ and FA++ series was increased by the addition of NaOH to the mixture water. The alkali content (in kg/m³, Na_2Oeq) of the concrete mixtures is as follows:

	FA content	0%	20%	30%
Alkali content	Control	3.78	--	--
	FA	--	3.02	2.65
	FA+	--	4.20	3.68
	FA++	--	--	4.12

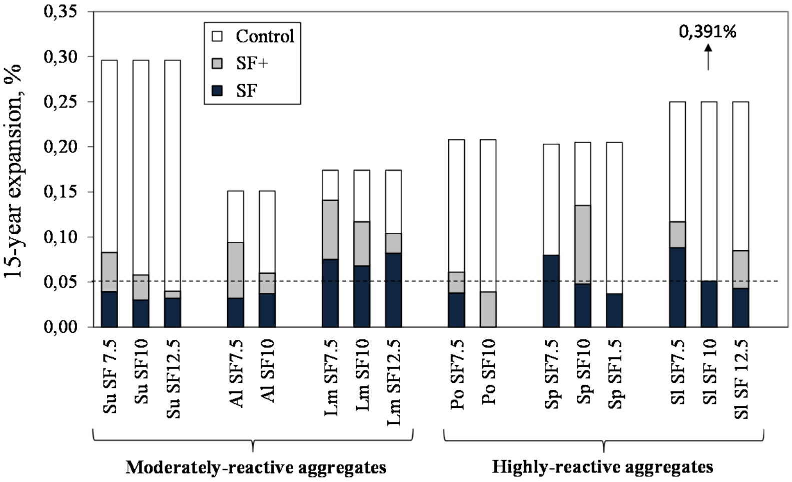


Figure 10: Effect of alkali addition on the 15-year expansion of silica fume exposure blocks. The alkali content corresponding to the <u>cement</u> part in the SF+ series was increased by the addition of NaOH to the mixture water. The alkali content (in kg/m³, Na_2Oeq) of the silica fume concrete mixtures is as follows:

SF content →		0%	7.5%	10%	12.5%
Alkali content	Con	3.78	--	--	--
	SF	--	3.50	3.40	3.31
	SF+	--	4.86	4.73	4.59