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Field and Laboratory Investigations on the Use of Fly Ash and Li-Based Admixtures to Prevent ASR in Concrete

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ABSTRACT

Since the early 1990's, CANMET (Department of Natural Resources Canada) is carrying out a comparative field and laboratory research program to investigate the efficacy of laboratory test procedures for properly predicting the long-term efficacy of supplementary cementitious materials (SCM) in controlling expansion due to alkali-silica reaction (ASR). Binary and ternary concrete systems, i.e. fly ash (Class F), lithium-based admixtures, fly ash / Li-based admixtures, were selected with a variety of alkali-silica reactive aggregates. The expansive behaviour of the various combinations listed above was investigated in the laboratory using concrete prisms stored under accelerated test conditions (38^{o}C and 100% RH). Exposure blocks cast from the above mixtures were placed outdoors at the CANMET facilities located in Ottawa (Canada). This paper compares the results of expansion testing in the laboratory against that of exposure blocks after 15 years outdoors. The results are also analysed in view of providing recommendations for the use of such materials / combinations for the manufacture of concrete that will be at a minimum risk of developing deleterious expansion and cracking due to ASR.

Keywords: Alkali-silica reaction, preventive measures, concrete durability, laboratory and field testing.

1.0 INTRODUCTION

ASR is a well-known phenomenon that deleteriously affects the durability and serviceability of concrete structures worldwide. Tremendous R&D efforts have resulted in the development of practices/guidelines that are now available to practitioners for selecting preventive measures against ASR. These generally include a *performance* approach based on laboratory testing, and a *prescriptive* approach following a risk analysis that includes factors such as the reactivity level of the aggregate, the type, size and exposure conditions of the structure, and the composition of cementitious materials proposed for use (Nixon and Fournier, 2017). The accelerated mortar bar test (AMBT) and the concrete prism test (CPT) are the most widely use procedures for evaluating the potential alkali-reactivity of concrete aggregates and the effectiveness of preventive measures against ASR in the laboratory (CSA, 2014a; ASTM, 2013, 2014). Thomas *et al.* (2006, 2007) presented a critical review of these tests. The authors reported that the CPT is often considered as the most reliable test available for the above purposes; however, it remains critical to validate its reliability through comparative field performance evaluations.

2.0 SCOPE OF WORK

In the early 1990's, CANMET initiated a research program to evaluate the effectiveness of SCM and lithium-based products to control ASR expansion in concrete (Fournier and Malhotra 1996). A testing matrix was developed including a variety of reactive aggregates and cementitious materials from different parts of the world. Lithium-hydroxide monohydrate ($LiOH{\cdot}H_2O$) and lithium nitrate ($LiNO_3$) admixtures were also used in selected concrete mixtures, in combination or not with fly ash. From each of the above mixtures, concrete prisms and blocks were cast and their expansion and cracking development monitored using accelerated test conditions in the laboratory and natural exposure in the field.

3.0 MATERIALS

The reactive coarse aggregates used in this study correspond to extremely-reactive (NM) and moderately-reactive (Wy) gravels from the USA, and highly-reactive crushed aggregates from Canada (Con, Sp). A control non-reactive sand from Canada was used in all concrete mixtures (Table 1).

Table 1. Composition of the coarse (CA) and fine (FA) aggregates used in this study.

Type	ID	Reactivity level	Rock Type
CA	Wy	MR	Granite, amphibolite, rhyolite, sandstone
	Con	HR	Greywacke, argillite
	NM		Mixed volcanic, quartzite, sandstone
	Sp		Siliceous limestone
FA	Control	NR	Natural derived from granite

NR: non reactive; MR: moderately reactive; HR: highly reactive

Low- (C1) and high-alkali (C2) General Use portland cements from Canada were used in this study. ASTM Class F fly ashes from Canada (FA1) and the USA (FA2 & FA3) were selected. The properties of the cementitious materials are given in Table 2.

A synthetic resin type air-entraining admixture was used in all concrete mixtures. Reagent grade NaOH pellets were used in order to increase the total alkali content of a number of concrete mixtures to selected levels, as indicated in Table 3. Commercially available lithium hydroxide monohydrate ($LiOH\cdot H_2O$) powder (LiOH) and lithium nitrate solution (30% solid) (LiN) were used in selected concrete mixtures.

Table 2. Properties of the cements and SCMs.

Parameter	C1	C2	FA1	FA2	FA3
< 45 µm, %	93.1	93.5	78.2	71.5	74.5
Blaine, m^2/kg	410	400	262	273	n.a.
Sp. Gravity	3.14	3.06	2.46	2.41	2.28
SiO_2, %	21.15	21.42	41.72	50.16	59.15
CaO, %	60.35	62.39	2.06	2.39	7.45
Al_2O_3, %	4.00	5.08	19.7	26.84	19.13
Fe_2O_3, %	5.39	2.37	26.03	12.75	5.27
MgO, %	3.40	2.55	0.87	0.89	2.47
SO_3, %	2.46	3.11	1.08	0.78	0.18
LOI, %	2.25	2.50	3.38	2.80	0.18
Na_2O, %	0.13	0.22	0.79	0.26	2.50
K_2O, %	0.41	1.03	2.12	2.24	1.06
Na_2Oeq, %	0.40	0.90	2.18	1.73	3.20

4.0 MIXTURE PROPORTIONING

Table 3 gives the proportioning of the concrete mixtures manufactured. All mixtures were made with high-alkali cement C2, except for mixtures ConL and SpL that incorporated low-alkali cement C1. In accordance with CSA A23.2-28A (CSA, 2014b), a nominal cementitious materials content of 420 ± 10 kg/m^3 was used. Water-to-cementitious materials ratios ranging from 0.35 to 0.42 were obtained.

Mixtures were made with or without added alkalis. Mixtures where NaOH was added to increase the total alkali content to 1.25% (Na_2Oeq), per cement mass, are identified with a "+" in Table 3. Table 3 also gives the concrete alkali content, expressed in kg/m^3, Na_2Oe. For mixture ConFA30++, large addition of alkalis was used to further evaluate the beneficial effect of fly ash to control ASR expansion.

The dosage of lithium compounds was adjusted to the target molar ratio [Li]/[Na+K], based on the total concrete alkali content, as follows:

- Mixtures incorporating $LiOH\cdot H_2O$ at 100 and 150% of the "standard" dosage recommended by the manufacturer. The latter is 1 kg of $LiOH\cdot H_2O$ for every kg of Na_2Oeq in the mixture. Such a dosage, i.e. LiOH1.0 in Table 3, gives a [Li]/[Na+K] of 0.74. Mixture LiOH1.5 gives a [Li]/[Na+K] of 1.1.
- Mixtures incorporating LiN at 100 and 125% of the recommended dosage. The latter is 4.6 litres of liquid $LiNO_3$ (30% solid) for every kg of Na_2Oeq in the mixture. Such a dosage, i.e. LiN1.0 in Table 5, gives a [Li]/[Na+K] of 0.74. The [Li]/[Na+K] of the other mixtures made with LiN are given in Table 3.

Testing carried out in accordance with Standard Practice CSA A23.2-28A, i.e. for evaluating the effectiveness of lithium-based admixtures to control ASR expansion, normally requires to add NaOH to the mix water in order to raise the concrete alkali content to 1.25%, by cement mass. In this study, concrete mixtures incorporating LiOH and LiN only were made unboosted considering the highly to extremely reactive character of the aggregates Con and NM that were used in those mixtures.

Fly ash concrete mixtures were made at the 20 and 30% (FA20, FA30 in Table 3) cement replacement levels (by mass) of the cement C2. Several mix designs were made boosted and unboosted, for comparison purposes. "Ternary preventive" systems using combinations of LiN (50 and 75%) and fly ash (15 and 20%) were generally made with added alkalis (e.g. FA15LiN0.75+, FA20LiN0.75+), with the exception of mixture NMFA20LiN0.75. It is important to note, however, that when boosting the alkali content with NaOH, the lithium-to-alkali molar ratio [Li]/[Na+K] was still maintained to respect the dosage recommended by the manufacturer, i.e. those mixes also contained more lithium. All concrete mixtures were air-entrained; the target air content of 6 ± 1% was achieved in all cases.

Table 3. Characteristics of the concrete mixtures

Mix identification	Cement. Mat. (kg/m^3)				Alkali content (kg/m^3)	Lithium compound	
	Cem	FA (1)	Tot	w/c	Na_2Oe	(2)	(3)
NM	431	---	431	0.40	3.88	0.0	0.0
NMFA20+	337	84	421	0.38	4.22	---	---
NMFA30+	295	126	421	0.37	3.69	---	---
NMLiOH1.0	431	---	431	0.40	3.88	3.78	0.73
NMLiOH1.5	424	---	424	0.40	3.82	5.72	1.1
NMLiN1.0	426	---	426	0.39	3.85	*17.7*	0.75
NMLiN1.25	423	---	423	0.39	3.81	*21.9*	0.93
NMFA15LiN0.75+	358	63	421	0.38	4.48	*15.5*	0.56
NMFA20LiN0.50+	337	84	421	0.37	4.22	*9.7*	0.37
NMFA20LiN0.75	338	84	422	0.38	3.04	*10.5*	0.56
NMFA20LiN0.75+	337	84	421	0.38	4.22	*14.5*	0.56
Wy+	428	---	428	0.38	5.35	---	---
Wy FA20+	338	84	422	0.37	4.98	---	---
Wy FA30+	296	127	423	0.36	4.84	---	---
WyFA15LiN0.75+	362	64	426	0.36	4.53	*15.6*	0.56
WyFA20LiN0.50+	339	84	423	0.35	4.24	*9.7*	0.37
WyFA20LiN0.75+	339	85	424	0.36	4.24	*14.6*	0.56
ConL	430	---	430	0.40	1.72	---	---
Con	427	---	427	0.40	3.84	---	---
Con+	427	---	427	0.40	5.34	---	---
ConFA20	343	86	429	0.39	3.09	---	---
ConFA20+	341	85	426	0.39	4.26	---	---
ConFA 30	304	130	434	0.38	2.74	---	---
ConFA30+	304	130	434	0.38	3.80	---	---
ConFA30++	304	130	434	0.38	5.33	---	---
ConLiOH1.0	421	---	421	0.40	3.78	3.78	0.73
ConLiOH1.5	428	---	428	0.40	3.84	5.78	1.1
SpL	417	---	417	0.42	1.67	---	---
Sp	427	---	427	0.41	3.84	---	---
Sp+	418	---	418	0.42	5.23	---	---
SpFA20	338	84	422	0.39	3.04	---	---
Sp FA30	298	128	426	0.38	2.68		
SpFA30+	296	127	423	0.38	3.70	---	---
SpLiN1.25	420	---	420	0.39	3.78	*21.7*	0.93

(1) FA1 was used with aggregate Con; FA2 was used with aggregate Sp; FA3 was used with aggregates NM and Wy.
(2) LiOH: kg/m^3; *$LiNO_3$: L/m^3*.
(3) Lithium-to-alkali molar ratio: [Li] / [Na + K]

Fig. 1. Concrete blocks disposed on the CANMET outdoor exposure site

Fig. 2. Disposal of the concrete blocks, i.e. sitting directly on the ground or above ground

Fig. 3. Measurement on the longitudinal axis on the top of a concrete block (gage length is 500mm)

5.0 MANUFACTURE/TESTING OF SPECIMENS

One or two blocks, 0.40 x 0.40 x 0.70 m in size, were cast from each concrete mixture. For length-change monitoring, eight stainless steel studs, 9 mm in diameter by 75-mm long, were partially embedded in the concrete blocks. After 7 days in their mould covered with wet burlap, the specimens were de-moulded and transported to the outdoor exposure site on the CANMET facilities in Bells Corners near Ottawa, Canada (Fig. 1). For each mixture, the first block was placed directly on the compacted gravel while the second one was placed above ground, sitting on two 200 x 400 mm concrete cylinders cut lengthwise (Fig. 2). When only one block was manufactured from a given mix, the latter was placed directly on the ground. Length measurements are being taken on the longitudinal axis (2 readings) on the top and on both sides of the block (Fig. 3).

Three test prisms, 75 x 75 x 300 mm in size, were cast from every concrete mixture made in this study. In accordance with the CPT procedure, after 24 hours in the moulds at 23°C and 100% RH, the prisms were demoulded and their initial length measured. They were then stored at 38°C and R.H. > 95%. Length-change measurements were then performed at regular intervals up to 4 years. All mixtures were made between May and October to avoid placing specimens outdoors in cold weather conditions; similarly, length measurements are taken on each specimen over the period between May and October of each year; cloudy days are selected for measurements to avoid direct sun exposure and large temperature effects on the specimens.

6.0 TEST RESULTS

6.1 Laboratory specimens

Table 4 gives the expansion of concrete prisms after 2 and 4 years of storage at 38°C and R.H. > 95%.

Control concretes

All test prisms made from the high-alkali control concretes expanded significantly over the period of testing, with 1-year expansions of 0.090% (Wy+), 0.184% (Sp+), 0.212% (NM) and 0.221 (Con+). The expansion continued at a much slower rate after one year and up to the end of the 4-year testing period, largely due to the well-known effect of alkali leaching from the test prisms (Lindgård *et al.* 2013). Over the 4-year testing period, low-alkali test prisms ConL and SpL suffered limited expansion (< 0.040%).

Table 4. Expansion results for concrete prisms (38°C and 100% RH) and exposure blocks

Mix identification	Concrete Prism		Exposure blocks	
	2 years	4 years	10 years	15 years
NM	0.231	0.243	0.469	0.684
NMFA20+	0.085	0.114	0.331	0.421
NMFA30+	0.050	0.075	0.255	0.331
NMLiOH1.0	0.163	0.204	0.242	0.390
NMLiOH1.5	0.039	0.064	0.013	0.034
NMLiN1.0	0.032	0.037	0.151	0.355
NMLiN1.25	0.030	0.038	0.019	0.041
NMFA15LiN0.75+	0.093	0.111	0.243	0.345
NMFA20LiN0.50+	0.076	0.100	0.195	0.280
NMFA20LiN0.75	0.039	0.071	0.125	0.232
NMFA20LiN0.75+	0.056	0.061	0.160	0.267
Wy+	0.093	0.086	0.215	0.295
Wy FA20+	0.030	0.045	0.103	0.178
Wy FA30+	0.013	0.021	0.056	0.103
WyFA15LiN0.75+	0.033	0.051	0.093	0.159
WyFA20LiN0.50+	0.019	0.028	0.044	0.100
WyFA20LiN0.75+	0.021	0.031	0.028	0.072
ConL	0.006	0.022	0.048	0.145
Con	0.125	0.151	0.161	0.326
Con+	0.221	0.255	0.302	0.664
ConFA20	0.026	0.056	0.055	0.109
ConFA20+	0.040	0.089	0.057	0.129
ConFA 30	0.012	0.036	0.023	0.056
ConFA30+	0.020	0.052	0.034	0.068
ConFA30++	0.035	0.066	0.050	0.088
ConLiOH1.0	0.127	0.146*	0.096	0.226
ConLiOH1.5	0.029	0.037*	0.009	0.016
SpL	0.029	0.035	0.049	0.077
Sp	0.171	0.172	0.165	0.205
Sp+	0.207	0.211	0.216	0.297
SpFA20	0.019	0.023	0.040	0.062
SpFA30	-0.001	0.003	0.014	0.015
SpFA30+	0.007	0.013	0.017	0.036
SpLiN1.25	0.029	0.034	0.014	0.022

*Results at 156 weeks.

Concrete made with Li compounds (binary systems)

With the highly-reactive aggregates NM and Con, concrete prisms made at the standard dosage of lithium hydroxide (LiOH1.0) resulted in two-year expansions of 0.163 and 0.127%, respectively; increasing to 150% of standard dosage (LiOH1.5) reduced concrete prism expansions below or close to the 0.04% level at two years (Table 4).

In the case of the lithium nitrate, the use of molar ratios of 0.74 (LiN1.0) and 0.93 (LiN1.25) both contributed in reducing concrete prism expansion close to or below 0.040% at two years with the NM and Sp aggregates (Table 4). With the NM aggregate, it is interesting to note that increasing lithium dosage above the recommended level, i.e. NM LiN1.0 to NM LiN1.25, did not result in further reduction of concrete prism expansion.

Concrete incorporating fly ash (binary systems)

The use of ASTM Class F fly ash at the 20 and 30% replacement levels resulted in significant reduction of expansion compared to the control concretes; the highest two-year expansions of 0.085% and 0.050% were obtained for the mixtures NM FA 20+ and NM FA 30+, respectively (Table 4, Fig. 4). Test prisms cast from 20% and 30% fly ash concrete mixtures incorporating aggregates Wy, Con and Sp suffered expansions at two years that were close to or below 0.040%. Interestingly, raising the concrete alkali content from 3.80 (Con FA 30+) to 5.33 kg/m^3 (Con FA 30++) resulted in two-year concrete prism expansions still below the 0.040% expansion limit with the highly reactive Conrad aggregate (Fig. 4).

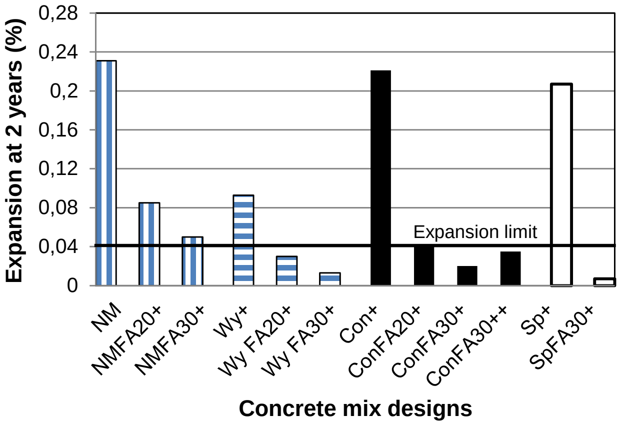

Fig. 4. Two-year expansions of concrete prisms made with reactive aggregates and fly ash. Mixtures were made with added alkalis, in accordance with CSA Standard Practice A23.2-28A

Concrete made with fly ash and Li (ternary systems)

The synergistic effect of combining LiN and fly ash (20% level) resulted in further reduction in expansion compared to using fly ash only (Fig. 5). For the aggregate NM, combining LiN and 20% fly ash resulted in expansion reductions ranging from 11 to 55% compared to 20% fly-ash mix. For the Wy aggregate, the reductions in expansion were about

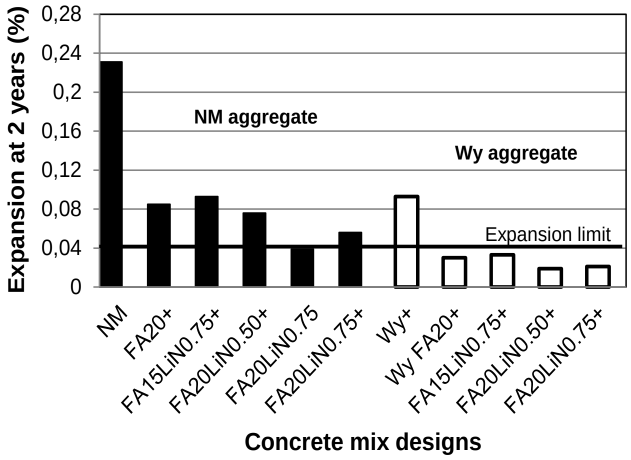

Fig. 5. Two-year expansions of concrete prisms made with reactive aggregates and combinations of fly ash and LiN. Mixtures were made with added alkalis (CSA Standard Practice A23.2-28A)

35%. With the Wy aggregate, the use of an additional dose of LiN over the 50% level, i.e. WyFA20LiN0.5+ to WyFA20LiN0.75+, did not result in further reduction of concrete prism expansion.

6.2 Exposure blocks

Table 4 gives the 10- and 15-year expansions of the exposure blocks.

Control concretes

High-alkali control blocks are showing expansions in excess of 0.20% after 15 years outdoors. Similar expansions of about 0.67% were obtained with the extremely reactive NM aggregate (unboosted mix NM) and the highly-reactive Con aggregate (boosted mix Con+) (Fig. 6). Similar 15-year expansions of about 0.30% were obtained for control mixtures Con, Sp+ and Wy+. Low-alkali control blocks ConL and SpL reached 0.145% and 0.077% expansion after 15 years of outdoor exposure, respectively.

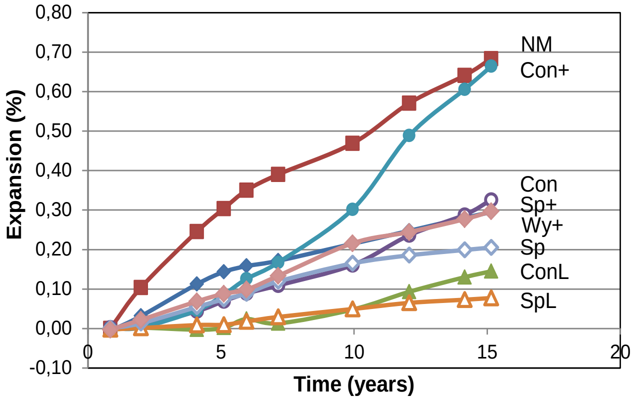

Fig. 6. Expansion of the control (high and low-alkali) concrete blocks exposed outdoors

6.3 Concrete incorporating lithium compound

Concrete made with Li compounds (binary systems)

With the extremely-reactive aggregate NM, the use of Li-based admixtures at the recommended [Li]/[Na+K] of 0.74 resulted in significant expansion reduction of expansion compared to the control concrete, i.e. 0.684% (NM) vs 0,390% (LiOH1.0) vs 0.355% (LiN1.0); however, the above expansions are still way above an acceptance limit (e.g. 0.05%). Increasing the Li dosage was however very beneficial and resulted in expansions ≤ 0.050% at 15 years (NMLiOH1.5 and NMLiN1.25) (Fig. 7).

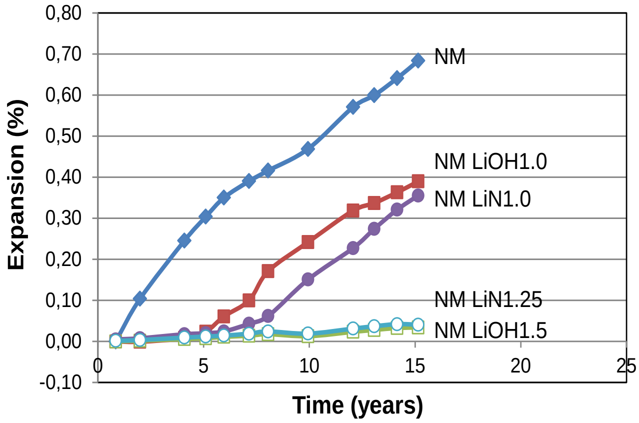

Fig. 7. Expansion of control and Li-based exposure blocks made with extremely reactive NM aggregate

Similarly, increasing the dosage of lithium hydroxide from 100 to 150% of the recommended dosage was found to control deleterious expansion due to ASR after 15 years in the case of concrete incorporating the highly-reactive Con aggregate (Fig. 8).

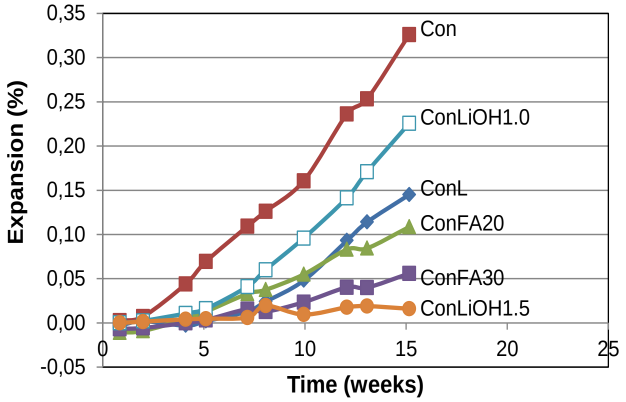

Fig. 8. Expansion of exposure blocks incorporating the highly-reactive Con aggregate, i.e. control, LiOH and fly ash concrete mixtures

Figures 9 to 13 illustrate the condition (extent of surficial cracking affecting the control exposure block NM and those incorporating lithium hydroxide

Fig. 9. Condition of control exposure block NM after 15 years outdoors (0.684% expansion)

Fig. 10. Condition of exposure block NMLiOH1.0 after 15 years outdoors (0.390% expansion)

Fig.11. Condition of exposure block NMLiOH1.5 after 15 years outdoors (0.034% expansion)

Fig. 12. Condition of exposure block NMLiN1.0 after 15 years outdoors (0.355% expansion)

Fig. 13. Condition of exposure block NMLiN1.25 after 15 years outdoors (0.041% expansion)

monohydrate and lithium nitrate after 15 years of exposure outdoors. The pictures clearly show the beneficial effect of increasing the dosage in lithium-based admixtures for reducing cracking due to ASR.

Concrete incorporating fly ash (binary systems)

Figure 14 shows that the use of fly ash contributed at reducing the 15-year expansion of exposure blocks made with the highly-reactive Con aggregate from 0.326% (Con) to 0.109% (ConFA20) and 0.056% (ConFA30). Interestingly, the 20% mix (even boosted) was slightly more effective than the low-alkali cement in reducing expansion of the exposure blocks. In the case of exposure blocks incorporating the Con aggregate and 30% fly ash, an increase in the concrete alkali content resulted in an increase in expansion, i.e. from 0.056% (ConFA 30) to 0.068% (ConFA30+) to 0.088% (ConFA30++); however, these expansion levels were still significantly lower than that of the boosted control block Con+ (Fig. 14).

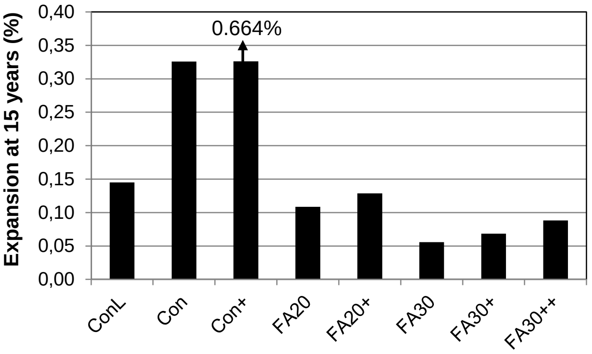

Fig. 14. 15-year expansions of exposure blocks incorporating the highly-reactive Con aggregate, i.e. control and fly ash concrete mixtures

With the highly-reactive Sp aggregate, using 20% fly ash resulted in large expansion reduction compared to the control, however not to < 0.05% (Fig. 15), similarly to the low-alkali cement. The use of 30% fly ash has however been effective in reducing expansion below 0.05% at 15 years (Fig. 15).

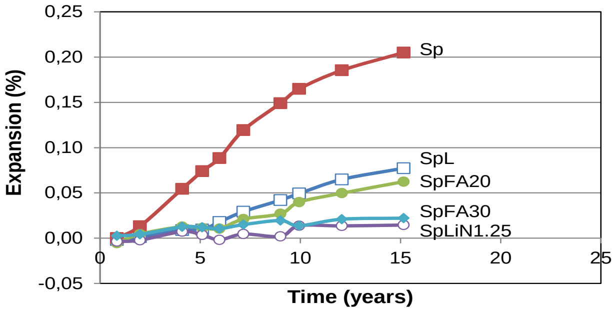

Fig. 15. 15-year expansions of exposure blocks incorporating the highly-reactive Sp aggregate, i.e. control, fly ash and LiN concrete mixtures

Concrete made with fly ash and Li (ternary systems)
Combining fly ash and lithium nitrate was efficient in further reducing expansion of concrete blocks incorporating the extremely reactive NM aggregates, compared to that obtained for the control and the binary mixtures incorporating fly ash only (Fig. 16).

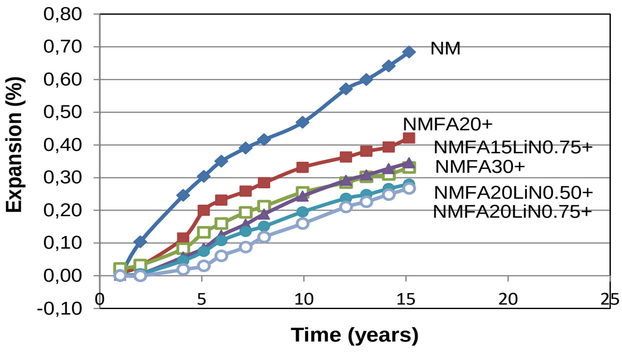

Fig. 16. Expansion of exposure blocks incorporating the extremely-reactive NM aggregate, i.e. control, binary fly ash concrete mixtures and ternary (fly ash + Lin) concrete mixtures

The ternary mixtures with 20% fly ash and LiN (NMFA20LiN0.5+ and NMFA20LiN0.75+) resulted in lower expansions than that obtained with the 30% fly ash mixture (NMFA30+). The expansion levels obtained are, however, still above the "acceptance level" of 0.05%, which may result from the fact that all that series of concrete mixtures were made with added alkalis. Similar results were obtained for the Wy reactive aggregate, as illustrated in Fig. 17 to 19.

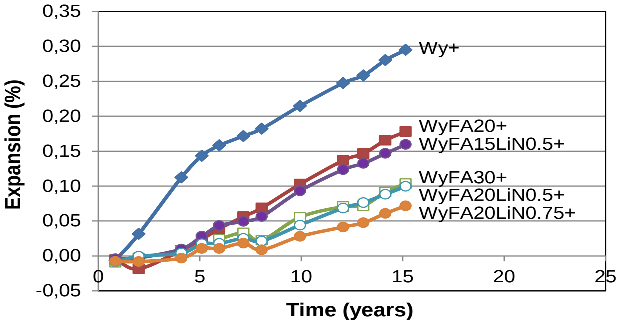

Fig. 17. Expansion of exposure blocks incorporating the moderately-reactive Wy aggregate, i.e. control, binary fly ash concrete mixtures and ternary (fly ash + Lin) concrete mixtures

Fig. 18. Condition of control exposure block Wy+ after 15 years of storage outdoors (0.295% expansion)

Fig. 19. Condition of block WyFA20LiN0.75++ after 15 years of storage outdoors (0.072% expansion)

7.0 DISCUSSION

7.1 Evaluating the potential alkali reactivity of concrete aggregates

The reactive character of the aggregates used in this study was well recognized through the expansion testing both in the laboratory and in the exposure blocks. Expansions in excess of the one-year CPT 0.04% limit for reactive aggregates (CSA, 2014b) were obtained for all aggregates. Interestingly, the moderately reactive aggregate Wy (one-year CPT expansion between 0.040% and 0.12%), induced a 15-year exposure block expansion similar to that obtained with the *highly-reactive* Spratt aggregate (about 0.30% - Sp+ and Wy+ in Fig. 6).

Exposure blocks made from low-alkali concretes ConL and SpL (original total concrete alkali content of only 1.7 kg/m^3, Na_2Oeq) reached 15-year expansions of 0.145% and 0.077%, respectively. McDonald *et al.* (2012) also reported the limited effectiveness of a low-alkali cement to control expansion of large concrete specimens (blocks and slabs) made with highly-reactive Spratt limestone This confirms that specifying low alkali cements as the only preventive measure in concrete made with highly-reactive aggregates is insufficient. Low-alkali control prisms ConL and SpL suffered only limited expansion (i.e. < 0.040%) after two and even four years of testing in the laboratory (38°C and 100% RH). This indicates that the CPT, in its current form, is not appropriate to evaluate the beneficial effect of low-alkali systems to control expansion in concrete due to ASR. Alkali leaching from test prisms is indeed a limiting factor for long-term expansion development in the test prisms. Lindgard at al. (2013) showed that using larger size concrete prisms (e.g. 100 x 100 x 500mm compared to typical ASTM/CSA size of 75 x 75 x 285 mm), helps in reducing alkali leaching.

7.2 Evaluating the effectiveness of preventive measures against ASR

Concrete incorporating fly ash (binary systems)
Large amounts of data highlighted the effect of various parameters on the effectiveness of fly ash in reducing ASR expansion in concrete, including their mineralogical and chemical composition, the type and reactivity level of the aggregates, the concrete alkali content and the exposure conditions to which the concrete is subjected (Thomas *et al.* 2017; Thomas, 2013).

In this study, three ASTM Class F fly ashes (low-calcium (2.0 – 7.5% CaO) and low alkali (1.7 – 3.2 Na_2Oeq) contents) were used with moderately to extremely reactive aggregates. Laboratory and field performance data generally agreed to show that the effectiveness of ASTM Class F (or low-calcium) fly ash in controlling ASR expansion vary according to the reactivity level of the aggregate and the proportion of the ash used.

For the extremely-reactive NM aggregate, both field and laboratory data indicate that 20% and even 30% of the fly ash FA3 used cannot control deleterious expansion due to ASR (Table 4; Fig. 16). It is to be noted, however, that a two-year concrete prism expansion of only 0.050% has been obtained in the laboratory for mixture NMFA30+, i.e. just above the limit of 0.040% suggested by CSA (2014a). Companion blocks exposed outdoors expanded by more than 0.30% after 15 years outdoors.

For the moderately-reactive aggregate Wy, the use of 20 and 30% of fly ash FA3 resulted in limited concrete prism expansion in the laboratory (Table 4); however, exposure blocks (although made with boosted alkalis) expanded by 0.18% and 0.10%, respectively, after 15 years outdoors, thus suggesting the limited effect of fly ash at those dosages for long-term prevention of ASR (Fig. 17). The CPT was thus found to largely underestimate the amount of expansion potentially developing in such systems under field conditions.

For both highly-reactive aggregates Con and Sp, exposure block expansions suggested that a 20% replacement level of a high-alkali cement will not be sufficient to prevent long-term deleterious expansion due to ASR (Fig. 8 and 15). The CPT was however unable to clearly demonstrate the limited effectiveness of such a fly ash dosage to prevent ASR expansion (Table 4). The use of 30% fly ash seemed to be efficient in preventing excessive expansion due to ASR with the above aggregates, both under laboratory and field conditions.

The above data are in general agreement with the recommendations of standard practice CSA A23.2-27A (prescriptive approach) (CSA 2014b), which suggests to use a minimum of 30% class F fly ash to prevent ASR in important civil concrete structures exposed to moisture when incorporating highly-reactive aggregates. Using extremely reactive aggregates such as the NM gravel in such concrete structures would require special preventive approach combining large amounts of fly ash (> 35% Class F) along with a reduced concrete alkali content (e.g. 1.8 or 1.2 kg/m^3, Na_2Oeq).

Concrete incorporating lithium compound
Since the pioneering work of McCoy and Caldwell (1951), several studies showed that lithium-based compounds can reduce significantly expansion due to ASR (Thomas *et al.*, 2017). The data generated in this study support information found in the literature that the effectiveness of the lithium compounds, i.e. $LiOH{\cdot}H_2O$ and $LiNO_3$, is very much related to the lithium-to-alkali molar ratio used (i.e. [Li]/[Na+K]). With the exception of concrete mixture NMLiN1.0, similar information (i.e. Pass/Fail) was obtained from both the field and laboratory tests on concrete

regarding the effectiveness of $LiNO_3$ and LiOH in controlling ASR expansion with the NM, Con and Sp aggregates (Fig. 20). Indeed, the above admixtures used at [Li]/[Na+K] of 0.74 (i.e. LiN1.0 and LiOH1.0) resulted in high concrete expansions with the above aggregates. On the other hand, increasing the LiN dosage to 125% of the recommended dosage (i.e. [Li]/[Na+K] of 0.93), and the LiOH dosage to 150% of the recommended dosage (i.e. [Li]/[Na+K] of 1.1) resulted in similar effectiveness in controlling ASR expansion (Fig. 20).

Tremblay *et al.* (2007) showed that the response to lithium of the reactive NM aggregate was generally better than that of highly-reactive aggregates Sp and Con, despite the extremely reactive character of the former. However, the results obtained in this study showed that the use of LiN dosage at a [Li]/[Na+K] of 0.93 was equally efficient in reducing expansion in concretes incorporating NM and Sp aggregates, while a LiOH dosage at a [Li]/[Na+K] of 1.1 was equally efficient in reducing expansion in concretes incorporating NM and Con aggregates (Fig. 20).

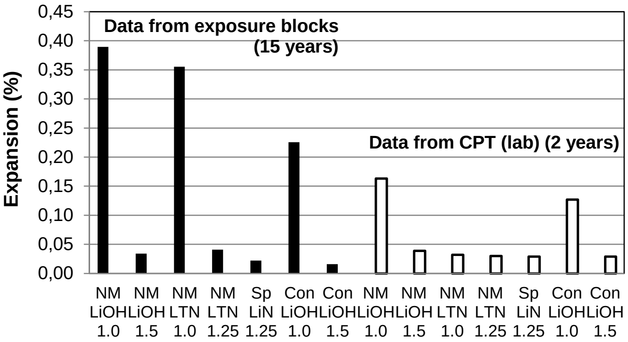

Fig. 20. Comparison between field and laboratory expansions for specimens incorporating Li-based compounds and reactive aggregates NM and Con

Concrete incorporating lithium and fly ash

Testing on concrete prism and exposure blocks confirmed the synergistic effect of combining $LiNO_3$ and fly ash (20% level), which resulted in further reduction in ASR expansion compared to the use of fly ash only (Table 4, Fig. 16,17). For a given fly ash content, the level of reduction was found to be a function of the lithium-to-alkali molar ratio used (e.g. expansion LiN0.5%+ > LiN0.75+), and of the concrete alkali content (e.g. expansion LiN0.75+ > LiN0.75) (Table 4).

Comparing CPT and exposure block data

Some of the test results obtained in this study suggest that a specific CPT expansion limit criteria of 0.040% at two years may not be universally indicative of the long-term field performance of every possible combinations of reactive aggregates – SCMs -with/without lithium-based admixtures. This can be seen in Fig. 21, which compares the 2-year CPT expansions and the 15-year expansions of exposure blocks. In this graph, when available, CPT expansions with boosted prisms were compared to that of unboosted blocks; in other cases, boosted prisms were compared to boosted blocks, and unboosted prisms to unboosted blocks. The data show the tendency of the CPT to underestimate field expansions, i.e. several data points are found in the lower right quadrant indicating excessive field expansions compared to lab expansions. Fournier *et al.* (2016) also reported such a trend based on a larger number of combinations of reactive aggregates and SCM (fly ash, slag, silica fume).

Tremblay *et al.* (2012) reported the results from the condition assessment of a 155m-long experimental pavement section of a bridge carrying Lomas Boulevard in Albuquerque (New Mexico, USA), and that was constructed in June 1992. The pavement section included the extremely-reactive natural gravel aggregates from two local sources (same as the NM aggregate used in the CANMET study) and eleven different concrete mixtures designed to evaluate various preventive measures against ASR.

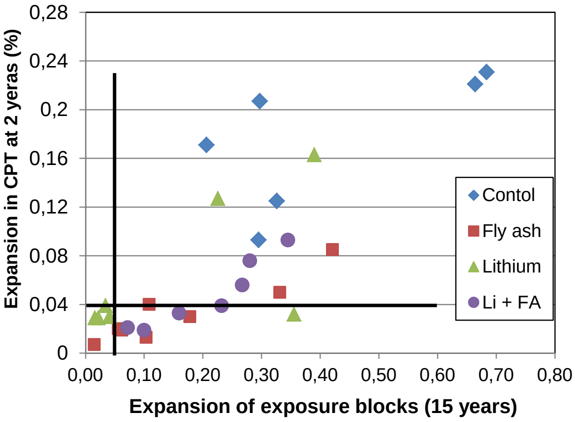

Fig. 21. Comparison between field and laboratory expansions for specimens tested in this study

Condition assessment of a concrete pavement incorporating fly ash and lithium-based admixtures

In addition to two control sections, five sections were made with fly ash, i.e. 20% Class F (2), 20% Class C (2) and 50-50 blend of Class C & F ashes. Lithium hydroxide monohydrate ($LiOH \bullet H_2O$) in powdered form was used in three sections at dosages of 0.5 percent ([Li]/[Na+K]=0.67 or 91% of the standard dose) or 1.0 percent ([Li]/[Na+K]=1.34 or 182% of the standard dose) by mass of portland cement. The total nominal cementitious materials and cement alkali contents were 395 kg/m^3 and approximately 0.55 percent of Na_2Oe, respectively

In addition to a visual survey, cores were extracted from the different sections and subjected to compressive strength and petrographic testing. The *Damage Rating Index* (DRI) method proposed by Grattan-Bellew and Mitchell (2006) was performed on polished concrete sections. The method consists in counting, under the stereomicroscope, the number of petrographic features of deterioration in a grid drawn on the section, including a minimum of 200 grid squares, 1 cm by 1 cm in size. The DRI represents the normalized value (to 100 cm^2) of the presence of petrographic features after the count of their abundance over the surface examined has been multiplied by selected weighing factors.

After 16 years in service, all sections displayed some cracking. The sections incorporating lithium and Class F fly ash were in the best condition and showed only localized cracking. Sections made with Class C ash, showed the worse surface condition. The lowest compressive strengths were obtained for cores extracted from Class C ash (15 MPa), control (26 MPa) and Class C-F ash (31 MPa) concretes. Other sections displayed strengths ranging from 35 to 42 MPa. The control and Class C fly ash concretes showed moderate to severe internal damage due to ASR (DRI values between 600 and 700). On the other hand, cores from concretes incorporating lithium and class F fly ash showed very limited internal ASR deterioration (DRI values between 100 and 150).

8.0 CONCLUSIONS

The effectiveness of the Concrete Prism Test for properly predicting the long-term efficacy of SCM and lithium-based admixtures to control expansion due to ASR was evaluated by comparing data generated in the laboratory against the expansion of larger size concrete specimens exposed outdoors.

Field performance data (i.e. 15-year exposure block expansions) generally showed that a minimum of 30% Class F fly ash is required for reducing expansion under an acceptable limit for concretes incorporating a high-alkali cement and highly-reactive aggregates (e.g. Sp and Con). Such a dosage is likely not sufficient with an extremely-reactive aggregate such as the NM gravel. The effectiveness of lithium compounds, i.e. $LiOH \cdot H_2O$ and $LiNO_3$, was found to be related to the lithium-to-alkali molar ratio used (i.e. [Li]/[Na+K]), with [Li]/[Na+K] of 0.93 ($LiNO_3$) and 1.1 ($LiOH \cdot H_2O$) being efficient in reducing expansions in exposure blocks incorporating the aggregates NM, Sp and Con under a 0.05% expansion level at 15 years. Testing data obtained from laboratory concrete prisms and from concrete specimens exposed outdoors confirmed the synergistic effect of combining $LiNO_3$ and fly ash (20% level) to control ASR expansion.

The CPT performed under CSA standard practice A23.2-28A may underestimate the amount of SCM required to control ASR when compared to data obtained on high-alkali concrete blocks exposed outdoors.

The results from the visual survey and the laboratory testing of cores extracted from concrete pavement sections in New Mexico (USA), after about 16 years in service, showed that the use of lithium-based products (LiOH at 0.67 and 1.34 molar ratio, [Li]/[Na+K]) and of about 20% class F fly ash was effective in reducing/controlling expansion and cracking in concrete pavement sections made with the highly-reactive NM (Shakespeare) aggregate material. It is to be noted that the above concretes incorporated a low-alkali cement.

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References

ASTM C 1778-14. 2014. Standard Guide for Reducing the Risk of Deleterious AAR in Concrete. Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

ASTM C1567-13. 2013. Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method). Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

CSA A23.2-28A. 2014a. Standard Practice for Laboratory Testing to Demonstrate the Effectiveness of Supplementary Cementing Materials and Chemical Admixtures to Prevent ASR in Concrete. CSA A23.1&A23.2-14 Concrete Materials and Methods of Concrete Construction. Canadian Standards Association (CSA), Mississauga, ON, Canada, 2014.

CSA A23.2-27A. 2014b. Standard Practice to Identify Degree of Alkali-Reactivity of Aggregates and to Identify Measures to Avoid Deleterious Expansion in Concrete. CSA A23.1&A23.2-14 Concrete Materials and Methods of Concrete Construction. Canadian Standards Association, Mississauga, ON, Canada.

Fournier, B., Malhotra, V.M. 1996. Reducing expansion due to alkali-silica reactivity. Concrete International (ACI), 18(3): 55-59.

Fournier, B., Chevrier, R., Bilodeau, A., Nkinamubanzi, PC, Bouzoubaa, N. 2016. Comparative field and laboratory investigations on the use of SCMs to control ASR in concrete. 15th Int. Conf. on alkali-aggregate reaction (AAR) in concrete, July 2016, Sao Paulo (Brazil), 10p.

Grattan-Bellew, P.E., Mitchell, L.D. 2006. Quantitative petrographic analysis of concrete – The Damage Rating Index (DRI) method, a review, 8th Int. CANMET-ACI Conf. on Recent Advances in Concrete Technology – M.A. Bérubé Symp. on AAR in Concrete, Montréal (Canada), May 2006, B. Fournier Editor, CANMET-MTL, 321-334.

Lindgård, J., Thomas, M.D.A., Sellevold, E.J., Pedersen, B., Andiç-Çakır, O., Justnes, H., Rønning, T.F. 2013. Alkali–silica reaction (ASR)—performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion, Cement and Concrete Research, 53 : 68-90.

MacDonald, C.A., Rogers, C.A., Hooton, R.D. The relationship between laboratory and field expansion – Observations at the Kingston exposure site for ASR after twenty years. 14th Int. Conf. on alkali-aggregate reaction (AAR) in concrete, May 2012, Austin (Texas)).

McCoy, W.J., Caldwell, A.G. 1951. New Approach in Inhibiting Alkali-Aggregate Expansion, ACI Journal, 22(9) : 693-706.

Nixon. P., Fournier, B. 2017. Chapter 2 – Assessment, testing and Specification. In Alkali-Aggregate Reaction – a World Review. Sims, I. and Poole, A. (Editors), CRC Press (Taylor & Francis Group), 768p.

Thomas, M.D.A., Fournier, B., Folliard, K.J., Ideker, J.H., Shehata, M. 2006. Test methods for evaluating preventive measures for controlling expansion due to ASR. Cement & Concrete Research, 36 : 1842-56.

Thomas, M.D.A., Fournier, B., Folliard, K.J.., Shehata, M., Ideker, J.H., Rogers, C.A. 2007. Performance Limits for Evaluating Supplementary Cementing Materials Using the Accelerated Mortar Bar Test. ACI Materials Journal, 104(2) : 115-122.

Thomas, M.D.A. 2013. Supplementary cementing materials in concrete. CRC Press (Taylor and Francis group), 190p.

Thomas, M.D.A., Hooton, R.D., Folliard, K.J. 2017. Chapter 4 – Prevention of Alkali Silica Reaction. In Alkali-Aggregate Reaction – a World Review. Sims, I. and Poole, A. (Editors), CRC Press (Taylor & Francis Group), 768p.

Tremblay, C., Bérubé, M.A., Fournier, B., Thomas, M.D.A., Folliard, K.J. 2007. Effectiveness of lithium-based products in concrete made with Canadian aggregates. ACI Materials Journal, 104(2):195-205.

Tremblay, S., Fournier, B., Thomas, M.D.A., Folliard, K.J. 2012. The Lomas Boulevard road test site, Albuquerque, NM. Case study on the use of preventive measures against ASR in new concrete. 14th Int. Conf. on alkali-aggregate reaction (AAR) in concrete, May 2012, Austin (Texas).