CANMET / INDUSTRY RESEARCH CONSORTIUM ON ALKALI-SILICA REACTIVITY (ASR)

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ABSTRACT

In 1991, CANMET initiated a major research project dealing with preventive measures against alkali-silica reactions (ASR) in concrete. The main objective of the above project is to develop a comparative field and laboratory engineering data base on the long-term effectiveness of supplementary cementing materials (SCM) in controlling and/or reducing expansion and cracking in concrete due to ASR. As part of this program, a number of organizations in the private and public sectors have joined CANMET in this research, and as a result an international research consortium has been formed.
Keywords: Alkali-aggregate reactivity, fly ash, granulated blast-furnace slag, preventive measures, silica fume, supplementary cementing materials.

INTRODUCTION

The Canada Centre for Mineral and Energy Technology (CANMET) has been active in the area of alkali-aggregate reactivity for the past 25 years. Earlier research was directed at identifying rock types in Eastern Canada which could be potentially reactive. In recent years, the research program has been expanded to evaluate the usefulness of various test methods in determining the potential alkali-reactivity of concrete aggregates, and to evaluate the effectiveness of various preventive measures against alkali-aggregate reactivity (AAR) (Malhotra & Fournier 1995). In 1991, CANMET initiated a major laboratory and field research program to develop an engineering data base on the long-term effectiveness of supplementary cementing materials (SCM) in reducing expansion and cracking in concrete due to ASR. As part of this program, CANMET invited a number of organizations in the private and public sectors to participate in this research; a consortium was then formed which now includes 15 partners from Canada, U.S.A., Mexico, Japan, and Australia (Fournier & Malhotra 1996).

In this study, a number of reactive aggregates have been selected to be tested in control concrete mixtures, and in mixtures incorporating various types and proportions of supplementary cementing materials (SCM) and other chemical additives. From each of these mixtures, specimens of different types and sizes were cast, and the expansion and cracking will be monitored over a minimum of three years in different accelerated storage conditions in the laboratory, and for ten years for those subjected to natural environmental conditions. The above combinations were also tested in ASTM C 1260 Accelerated Mortar Bar Test to evaluate the usefulness of this method in predicting the long-term effectiveness of SCM in controlling expansion due to AAR.

MATERIALS USED

Aggregates

A total of thirteen reactive coarse aggregates, eight from Canada, one from the U.S.A., three from Australia and one from Japan have been selected for this study. They represent different rock types showing various degrees of alkali-reactivity in concrete (Table 1). The fine aggregate used is non-reactive and of granitic origin.

Table 1: Petrography and results of the Accelerated Mortar Bar and Concrete Prism tests for the aggregates from Canada used so far in the mixing program.

Aggregates	Rock Type	Expansion (AMBT)* 14 days	Expansion (CPT)** 1 year
Gr (quarried)	Granite and granitic gneiss	n.a.	0.035
Su (gravel)	Sandstone, quartzwacke, arkose, greywacke and argillite	0.266	0.095
Po (quarried)	Siliceous sandstone	0.093	0.113
Al (gravel)	Sandstone, limestone, quartzite and fine-grained volcanics	0.293	0.113
Lm (quarried)	Siliceous and argillaceous limestone	0.259	0.133
Sp (quarried)	Siliceous limestone, chert	0.391	0.170
Con (quarried)	Greywacke	0.464	0.175
Spl (quarried)	Greywacke	0.463	0.271

* Accelerated Mortar Bar Method (CSA A23.2-25A; ASTM C 1260)

** Concrete Prism Test (CSA A23.2-14A M94)

Portland cements, SCM and chemical admixtures

High- and low-alkali ASTM Type I portland cements from Canada and Australia have been used in the program. The SCM consist of ASTM Type F fly ashes from Canada, the U.S.A., and Australia, silica fumes from Canada and the U.S.A. and granulated blast-furnace slags from Canada and Australia. A summary of the physical properties and the chemical composition of the cements and SCM used so far in the mixing program is given elsewhere (Fournier & Malhotra 1996).

A synthetic resin type air-entraining admixture was used in all the mixtures. A commercially available sulphonated, naphthalene formaldehyde condensate superplasticizer was used in high-volume fly ash (HVFA) and silica fume concrete mixtures.

MIXTURE PROPORTIONING

All supplementary cementing materials selected for this program were used as replacement, by mass, of the high-alkali cement. The replacement levels tested were 20, 25, 30, and 56% for fly ashes, 7.5, 10, and 12.5% for silica fume, and 35, 50, and 65% granulated blast-furnace slags. For practical reasons, the SCM were used according to regional considerations, i.e. local reactive aggregates being used with SCM available in the regional market.

The nominal cementitious materials content for the concrete mixtures made in this study was 420 ± 10 kg/m^3, except for the high-volume fly ash (HVFA) mixtures (i.e. those mixtures incorporating 56% fly ash) for which the total cementitious materials content was 375 ± 10 kg/m^3. Effective water-to-cementitious materials ratios ranged from 0.37 to 0.42 for all the mixtures except that for the HVFA mixtures for which the value was 0.32. A series of concrete mixtures incorporating selected reactive aggregates were made using a total cementitious materials content of 225 kg/m^3, a maximum size coarse aggregates of 50 mm, and a water-to-cementititous materials ratio between 0.60 and 0.65. This was done to reflect mass concrete for use in hydro-electric dams.

For a selected number of mixtures, reagent grade NaOH pellets were added to the mixing water in order to increase the total alkali content corresponding to the cement part of the concrete system to 1.25% Na_2O equivalent. All the concrete mixtures were air-entrained with the target air content being 6 ± 1%. The dosage of the superplasticizer in the silica fume and HVFA concrete mixtures was adjusted to give desired workability.

Table 2: Physical Properties and Chemical Analysis of the Cements and Supplementary Cementing Materials Used so Far in the Mixing Program

	Cements		Fly Ashes		Blast	Silica
	C1 Low Alkali	C2 High Alkali	FA 1 Canada	FA 2 (U.S.)	Furnace Slag Canada	Fume Canada
A. Physical Tests						
Fineness • < 45 μm, %	93.11	90.79	78.19	71.54	98.96	97.48
• Blaine, m^2/g	410	399	262	273	436	...
Specific Gravity, g/cm^3	3.14	3.11	2.46	2.41	2.92	2.15
Compressive Strength, 28 days, MPa	47.3	41.5				
Pozzolanic Activity Index, 28 days, %			90.0	93.9	101.7	118.7
B. Chemical Analysis, %						
Silicon dioxide (SiO_2)	21.15	20.15	41.72	50.16	35.7	93.6
Calcium oxide total (CaO)	60.35	61.72	2.06	2.39	34.3	0.50
Aluminum oxide (Al_2O_3)	4.0	5.52	19.7	26.84	9.6	0.06
Ferric oxide (Fe_2O_3)	5.39	2.59	26.03	12.75	0.55	0.45
Magnesium oxide (MgO)	3.40	2.19	0.87	0.89	14.1	0.67
Sulphur oxide (SO_3)	2.46	4.98	1.08	0.78	3.69	0.32
Loss on ignition	2.25	1.54	3.38	2.80	1.59	2.26
Sodium oxide (Na_2O)	0.13	0.18	0.79	0.26	0.53	0.16
Potassium oxide (K_2O)	0.41	1.09	2.12	2.24	0.42	0.85
Alkalies, (Na_2O equiv.)	0.40	0.90	2.18	1.73	0.81	0.72

FIELD AND LABORATORY TESTING OF SPECIMENS

Laboratory test specimens

A number of concrete cylinders, 100 by 200 mm in size, and concrete prisms, 75 by 75 by 300 mm in size, were cast from each one of the mixtures. Concrete cylinders for compressive strength determination at the ages of 7, 28, 91 days and at later ages, i.e. one, two, and > two years were placed in a lime-saturated water bath for long-term storage at room temperature, i.e. 23 ± 2°C.

The concrete prisms, in sets of three, were tested in the following conditions: (A), 38°C and relative humidity > 95% (control condition), (B), 1N NaOH solution at 38°C, (C), 1N NaOH solution at 80°C, and (D), 5% NaCl solution at 38°C. The length change of the concrete prisms in each of the above storage conditions is being monitored at the ages of 1, 2, 4, 8, 13, 18 26, 39, 52 weeks, and at every three months after up to three years. Petrographic examination of the prisms is also performed to monitor the development of external signs of deterioration.

Test specimens for field exposure conditions

Two blocks, 0.40 by 0.40 by 0.70 m in size, and one slab, 0.70 by 0.70 by 0.15 m in size, were cast from each of the above concrete mixtures. For monitoring the length changes, eight stainless steel threaded studs, 9 mm in diameter by 75 mm long, were partially embedded in the concrete prisms; in the case of concrete slabs only four studs were embedded.

The large prisms and slabs were installed on a gravel pad consisting of a minimum of 0.3 m of well-compacted 0-25 mm crushed limestone material; the first prism is placed directly on the gravel while the second one is placed above ground, on two 200 mm in diameter by 0.40 m long concrete cylinders cut lengthwise (Fournier & Malhotra 1996). The concrete slabs are placed directly on the compacted gravel pad, with granular material being placed around and between each of them so that only the top surface of the slab is exposed (Fournier & Malhotra 1996).

A number of blocks made incorporating selected reactive aggregates and SCM were transported to Treat Island, Maine, U.S.A., for long-term exposure to severe marine environment (Fig. 1D). Slabs were also made from a selected number of concrete mixtures and were placed in compacted 0-25 mm granular material so that only their top surface was exposed; these were made to evaluate the effect of de-icing salt applications on the acceleration of AAR (Fournier & Malhotra 1996).

TEST RESULTS

Since no expansion data are currently available from the field testing program, the following paragraphs will summarize the results obtained so far from the laboratory investigations.

Compressive Strength Testing

The main conclusions for the compressive strength determinations performed so far as part of this study are summarized below:

- Compressive strengths were generally higher for test cylinders made from control mixtures incorporating the low-alkali cement than for those made with the high-alkali cement. Slight to significant reductions in compressive strengths were often observed with the addition of NaOH to the mixing water. Such results have also been reported previously (Shayan & Ivanusec 1989).
- As expected, compressive strengths of fly ash concretes are generally lower than that of control mixtures incorporating the high-alkali cement at early ages, with the difference decreasing with time. Higher compressive strengths are generally obtained with high-volume fly ash (HVFA) concretes than with the corresponding control mixtures at the same ages, except at 7 days. The difference in the compressive strengths of fly ash concretes with and without added alkalies was not found to be that pronounced at the 20% replacement level, being generally within 2 MPa. Significant reductions in the compressive strengths, i.e of 8 to 10 MPa, were noticed when large amounts of alkalies were added to concrete mixtures incorporating 30% fly ash.
- The compressive strengths obtained for the concrete mixtures incorporating 35% slag were similar to those obtained for the control mixtures made with the high-alkali cement; however, the values for the 35% slag concretes were significantly higher than those for the mixtures incorporating 50 or 65% slag. The difference in the compressive strengths between the 35% slag concrete mixtures and both the 50 and 65% slag mixtures was also found to increase with time for a given aggregate. The addition of NaOH does not have a clear effect on the compressive strength of the slag concretes.
- For a given aggregate, the compressive strength values obtained for the silica fume concrete mixtures were generally similar or slightly higher than those obtained for the control concrete mixtures made with the high-alkali cement. Also, for a given aggregate and a given age, only small differences in the compressive strength values, i.e. within 2 to 3 MPa, were obtained between the concrete mixtures incorporating 7.5, 10 or 12.5% silica fume. The addition of alkalies seems to have no significant effect on the compressive strengths of most silica fume concretes.

AAR Concrete Prism Expansion Testing

According to Appendix B of Canadian Standards A23.1-M94, the most suitable method for assessing the efficacy of supplementary cementing materials in reducing expansion due to AAR is the concrete prism test. Current experience is that a testing period of two years (with a 0.04% expansion limit) is sufficient for the evaluation of concretes containing fly ash or slag but particular attention should be paid to the rate of expansion toward the end of the testing period (Duchesne & Bérubé 1992, Thomas et al. 1992). Longer testing periods are required to assess the performance of concretes containing silica fume (Bérubé & Duchesne 1992, Oberholster 1989).

The immersion testing in the 1N NaOH and the 5% NaCl solutions at 38°C were used to determine if better control on the storage or testing conditions could be achieved by using immersion test conditions. No expansion limits are currently available for the above immersion tests at 38°C. The immersion testing in 1N NaOH solution at 80°C has been suggested for reducing the proposed testing time period for AAR. The test is very severe; its real significance and the expansion limits to be used are still open to debate.

The expansion test data obtained in the different storage conditions were analysed and compared in order to determine a series of expansion limits at specific ages; these were then used to evaluate the effectiveness of the various cementitious systems investigated in controlling ASR. The test results are summerized in Table 3.

The significant observations from the length change measurements performed so far are as follow:

- Increasing expansion with increasing alkali content in the concrete mixture is generally observed for control test prisms stored at 38°C and R.H. > 95% (Fig. 2A). Test prisms cast from the control mixtures incorporating the high-alkali cement and added alkalies generally expanded significantly more when tested at 38°C and R.H. > 95% than when immersed in the 1N NaOH solution at 38°C (Fig. 2A vs 2B).
- Test prisms cast from the mixtures incorporating the low-alkali cement generally gave the highest expansion values among the control mixtures when tested in 1N NaOH at 38°C (Fig. 2B). Test prisms made with the high-alkali cement and added alkalies generally gave the lowest expansion levels among the control mixtures when tested in 1N NaOH at 38°C (Fig 2B).
- Expansion values obtained for test prisms stored in the 5% NaCl solution were always found to be significantly less than those obtained for the companion series of test prisms stored either at 38°C and R.H. > 95% or in 1N NaOH solution at 38°C.
- Concrete prisms and mortar bars incorporating 30 or 56% fly ash invariably met the expansion limits proposed for the different test conditons used in this program (Table 3). Test prisms cast from the concrete mixtures incorporating the highly reactive Spl greywacke and 20% fly ash show a slow but steady increasing expansion during the first 104 weeks of testing both at 38°C, R.H. > 95% and in 1N NaOH at 38°C (Fig. 2C and 2D; Table 3). Additional testing will be performed to determine if the failure of the 20% fly ash system with the Spl aggregate was due to the particular composition of the fly ash used or due to the high reactivity level of the aggregate; however, these results confirm previous CANMET observations that indicated that a minimum of 30% fly ash is generally required to control deleterious expansion with highly-reactive aggregates (Malhotra & Fournier 1996).
- None of the test specimens cast from the 50 and 65% slag concrete or mortar mixtures have reached expansions greater than the expansion limit proposed for the different test conditions (Table 3). The use of 35% slag is not considered appropriate for concretes incorporating a highly-reactive aggregate (such as the Sp limestone); however, it may control adequately deleterious expansion with marginally reactive aggregates (such as the Su gravel) (Table 3).
- Expansions for the silica fume concrete test prisms subjected to the various storage conditions were generally found to decrease with increasing silica fume content. Between 7.5 and 10% silica fume seems necessary to reduce deleterious expansion of concrete prisms or mortar bars under the proposed expansion limits for marginally-reactive aggregates such as the Lm limestone and the Su gravel; however, 10% silica fume does not seem to control deleterious expansion with moderately- to highly-

reactive aggregates, such as the Po sandstone, the Sp limestone and the Spl greywacke (Fig. 2E and 2F; Table 3).

- The accelerated mortar bar test, using an expansion limit of 0.10% at 14 days, generally gives a good indication of the effectiveness of SCM in controlling expansion due to ASR; however, there were some exceptions as indicated in Table 3. This 0.10% expansion limit has also been proposed by Davies & Oberholster (1987) and Duchesne & Bérubé (1992).

CONCLUSIONS

Laboratory test results obtained so far have confirmed the beneficial effect of supplementary cementing materials in reducing expansion due to AAR in concrete. The effectiveness of these materials depends on several factors, including the chemical composition of the SCM and the potential alkali-reactivity of the aggregates.

CSA A23.2-14A Concrete Prism test seems satisfactory for evaluating the effectiveness of SCM in reducing expansion due to AAR; however, the two-year testing period is considered long. Testing is currently underway to evaluate the usefulness of other accelerated concrete and mortar methods for predicting the long-term effectiveness of SCM in controlling the expansion due to AAR.

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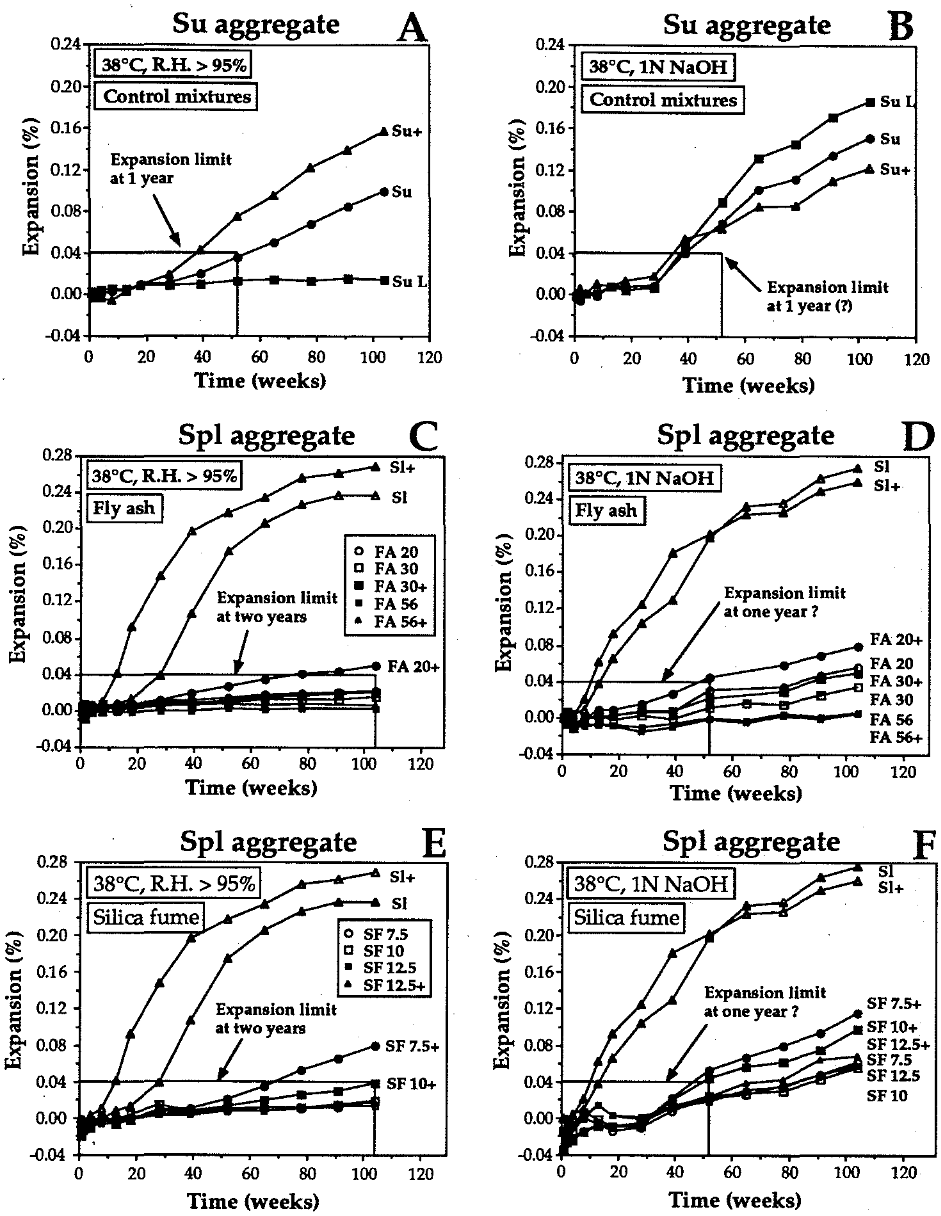

Fig. 2 Expansion curves for concrete prisms cast from concrete mixtures incorporating the Su (A&B) and Spl (C to F) aggregates.

A. Control mixture; Storage condition A: 38℃ and R.H. > 95%
B. Control mixture; Storage condition B: 1N NaOH solution at 38℃
C. Fly ash mixture; Storage condition A: 38℃ and R.H. > 95%
D. Fly ash mixture; Storage condition B: 1N NaOH solution at 38℃
E. Silica fume mixture; Storage condition A: 38℃ and R.H. > 95%
F. Silica fume mixture; Storage condition B: 1N NaOH solution at 38℃

Table 3: Summary of the Laboratory test results obtained in this study

Expansion of controls in ≠ storage conditions (see below):		**Aggregate Types**																			
		Limestone Lm				**Gravel Su**				**Sandstone Po**				**Limestone Sp**				**Greywacke Spl**			
Concrete Prism (condition A):		0.087% (2 years)				0.157 (2 years)				0.226% (2 years)				0.171% (2 years)				0.269% (2 years)			
Concrete Prism (condition B):		0.070 (1 year)				0.063 (1 year)				0.072 (1 year)				0.097 (1 year)				0.202 (1 year)			
Concrete Prism (condition C):		0.124% (8 weeks)				0.160% (8 weeks)				0.281% (8 weeks)				0.201% (8 weeks)				0.190% (8 weeks)			
Mortar Bar (condition D):		0.173 (14 days)				0.278 (14 days)				0.093 (14 days)				0.391 (14 days)				0.463 (14 days)			
Cementitious Materials		Testing condition				Testing condition				Testing condition				Testing condition				Testing condition			
Type	%	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Fly Ash	20					OK	OK	OK	OK					OK	OK	OK	•	•	•	OK	OK
FA 1: Po & Spl	30					OK	OK	OK	OK	OK	OK	OK		OK	OK	OK	OK	OK	OK	OK	OK
FA 2: Su & Sp	56					OK	OK	OK	OK					OK	OK	OK	OK	OK	OK	OK	OK
Slag	35					OK	OK	OK	•					•	•	•	•				
	50					OK	OK	OK	OK					OK	OK	OK	OK				
	65					OK	OK	OK	OK					OK	OK	OK	OK				
Silica Fume	7.5	•	OK	•	OK	OK	OK	OK	•	•	OK	•		•	•	•	•	•	•	•	•
	10	OK	OK	•	OK	OK	OK	OK	OK	•	OK	•		•	•	•	•	•	•	OK	•
	12.5	OK	OK	•	OK	OK	OK	OK	OK					OK	OK	OK	OK	OK	OK	OK	OK

Testing Condition and expansion limits:

(A): Concrete Prisms at 38°C, R.H. > 95%; Expansion limit of 0.04% at two years.

(B): Concrete Prisms at 38°C, in 1N NaOH solution; Expansion limit of 0.04% at one year.

(C): Concrete Prisms at 80°C, in 1N NaOH solution; Expansion limit of 0.04% at 8 weeks.

(D): Mortar bars at 80°C, in 1N NaOH solution; Expansion limit of 0.10% at 14 days.

•: The combination tested failed to meet the expansion limit suggested for this test condition

OK: The combination tested met the expansion limit suggested for this test condition