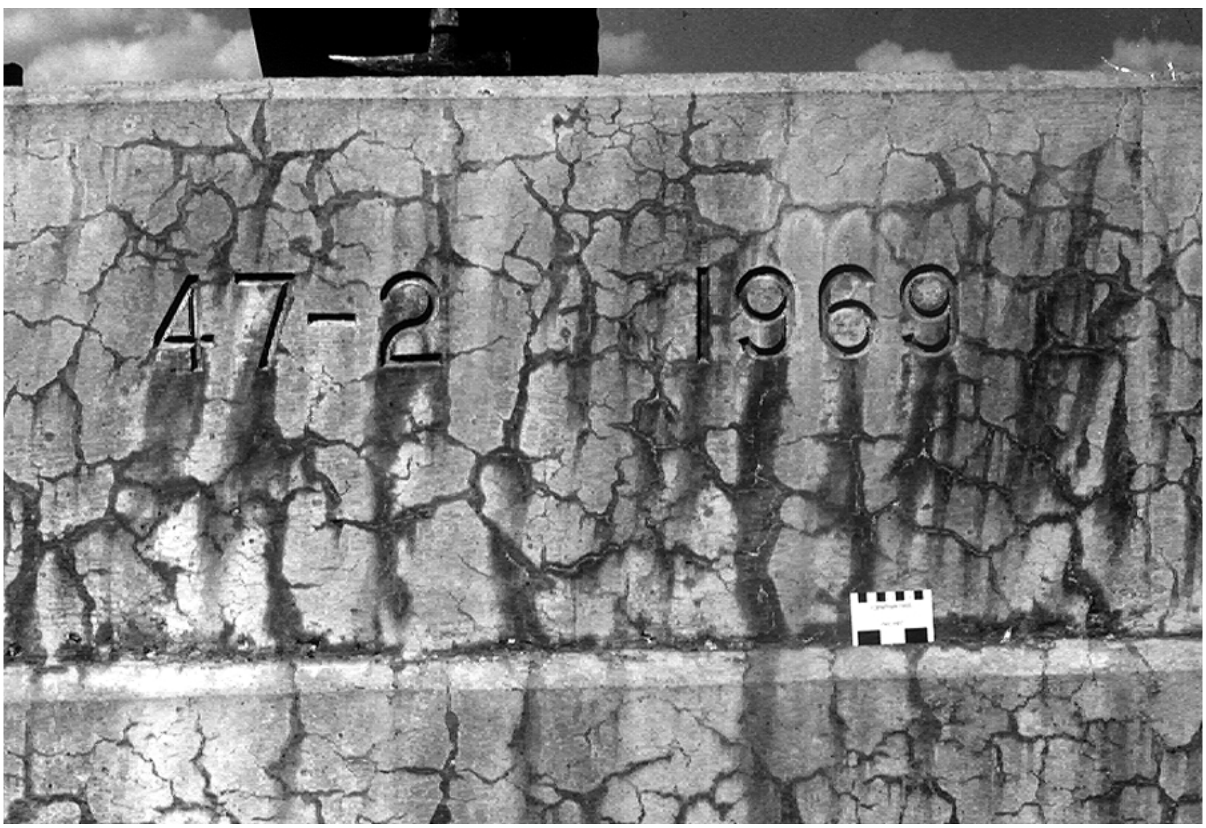
CANMET/Industry Research Consortium on Alkali-Aggregate Reactivity in Concrete

Technical Report



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Technical Report, December 2001

Prepared by
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REPORT SUMMARY

The alkali-silica reaction (ASR) is a deleterious chemical reaction that can result in the deterioration of concrete structures. This report presents the results of an R&D study, funded by a broadly-based multi-national industry consortium, that is developing an engineering data base on the long-term effectiveness of fly ash and other supplementary cementing materials (SCMs) in counteracting ASR in concrete.

Background
For long-term durability, the aggregates used in concrete must be physically strong and chemically inert. The alkali-silica reaction can develop between some siliceous mineral phases of aggregates and the alkali hydroxides of the concrete pore fluid, resulting in the formation of secondary products that create expansion and cracking of the concrete. This phenomenon was recognized first in the United States in the 1940s. A number of highway pavements, bridge structures, and hydraulic dams in Canada and the United States have been and still are badly affected by ASR: the amount of money potentially involved in the rehabilitation of such structures will be several hundred million dollars. The literature reports significant reduction of ASR problems when concrete is made with 30% ASTM Class F fly ash or 50 to 65% slag (as replacement by mass of the cement).

Objective
To develop an engineering database on the long-term effectiveness of supplementary cementing materials like coal fly ash in reducing and/or controlling the expansion and cracking of concrete due to Alkali-Aggregate Reactivity.

Approach
In 1991, the Canada Centre for Mineral and Energy Technology (CANMET) initiated a study of the long-term effectiveness of SCMs in reducing expansion and cracking in concrete due to AAR. The research team selected for testing a series of reactive coarse aggregates from Canada, the United States, and Australia, representing the different rock types and varying degrees of alkali-reactivity found in concrete. As a fine aggregate, they used a non-reactive type derived from granite. As a control, they used high and low-alkali ASTM Type I Portland cements from Canada and Australia. The team used coal fly ashes from Canada, USA, and Australia, in addition to silica fumes and granulated blast-furnace slags from Canada, Australia, and the United States. Fly ashes replaced cement at replacement levels of 20, 25, 30, and 56%; silica fume at 7.5, 10, and 12.5% levels; and granulated blast furnace slags at 35, 50, and 65% levels. The team obtained effective water-to-cementitious materials ratios ranging from 0.37 to 0.42 for all mixes with the exception of the high volume fly ash concrete mixes where the ratio was 0.32.

All concretes were air-entrained, with superplasticizer being used in silica fume and high-volume fly ash concretes. The team cast a series of concrete test specimens and conducted laboratory and field exposure tests on them.

Results
Various test methods are used to determine the degree of ASR attack on concrete by measuring the expansion of the concrete under different laboratory conditions. CANMET made a comparative evaluation of the laboratory test data and expansions measured on test beams and slabs subjected to outdoor conditions at CANMET outdoor exposure site located in Ottawa, Canada.

The results showed that the selection of efficient preventive measures against AAR should be done with the appropriate knowledge of the composition of the SCMs and the reactivity level of the aggregate.

EPRI Perspective
Alkali-Silica Reactivity is one of the leading causes of concrete deterioration. Control methods typically consist of (1) selective quarrying for non-reactive aggregates, (2) dilution of reactive aggregates with non-reactive ones, (3) use of low-alkali cements, and (4) use of supplementary cementing materials like coal fly ash. Given the unavailability of low-alkali cements in most areas, use of SCMs is generally the most cost-effective approach. During the next phase of the project additional subbituminuous coal ashes (ASTM Class C ashes) will be tested.

Keywords
Alkali-Aggregate Reactivity
ash use
Alkali-Silica Reactions
Concrete durability
Concrete deterioration

ABSTRACT

In 1991, CANMET initiated a major research project dealing with alkali-aggregate reactions (AAR) in concrete. As a part of this program, a number of organizations in the private and public sectors were invited to participate in this research, and as a result an international research consortium was formed.

The main objective of the above project, which is a comparative field and laboratory study, is to develop an engineering data base on the long-term effectiveness of fly ash and other supplementary cementing materials (SCM) in controlling and/or reducing expansion and cracking in concrete due to AAR.

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 a number of factors, including the chemical composition of the SCM and the potential alkali-reactivity of the aggregates.

The data obtained to date for companion concrete specimens subjected to outdoor exposure, at CANMET site in Ottawa, generally confirm the test data obtained in the laboratory. Monitoring of concrete beams and slabs is still being carried out to confirm the long-term performance of the various concrete mixtures and combinations under test.

ACKNOWLEDGMENTS

The study described in this report was carried out for the CANMET/Industry International Research Consortium on Alkali-Silica Reaction, of which the Electric Power Research Institute (EPRI) is a member. The authors wish to thank EPRI for the partial funding and the support of this work and, in particular, EPRI Project Manager, Dean Golden, for his enthusiasm and guidance.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Background

For long-term durability, aggregates used in concrete must be physically durable and chemically inert. A series of studies performed since the beginning of the 1940's has shown that a deleterious chemical reaction can develop between reactive siliceous mineral phases present within some aggregates and the alkali hydroxides (NaOH and KOH) of the concrete pore solution. This so-called *alkali-silica reaction* (ASR) produces secondary reaction products which expand and cause cracking of the cement paste, that in turn, results in the deterioration of concrete elements or structures.

A number of highway pavements, bridge structures, hydraulic dams and other concrete elements all over the world are showing durability and serviceability problems due to ASR; funds needed for the rehabilitation and partial reconstruction of such structures are in the order of several hundred millions of dollars. For example, in the case of the Mactaquac dam in New Brunswick, Eastern Canada, about 50 million dollars have been spent to date in the monitoring and repair activities that would not have been needed if the dam had not been affected by ASR.

When for some economical or geographical reasons a source containing reactive aggregates has to be used for constructing a new concrete structure, it is imperative to take efficient measures which will reduce the risk of future deterioration due to ASR. The use of supplementary cementing materials (SCMs) such as fly ash and granulated, blast-furnace slag is probably one of the most attractive preventive measure against ASR; however, the efficiency of SCMs in counteracting ASR in concrete can vary widely, and depends on many factors such as the nature and the composition of the materials involved, the reactivity level of the aggregates and the proportion of SCMs in concrete mixtures. The published results of laboratory tests, in general, indicate that about 30% ASTM Class F fly ash and 50 to 65% slag (as replacement by mass of the cement) are necessary to counteract alkali-silica reaction; however, these results have often been obtained using mortar bars containing extremely reactive materials such as opal or some artificial materials and are not necessarily applicable to all reactive aggregates and supplementary cementing materials.

This Study

The Canada Centre for Mineral and Energy Technology (CANMET) has been active in the area of alkali-aggregate reactivity for the past 25 years [1]. Earlier research was directed at identifying rock types in Eastern Canada which could be potentially reactive. In 1991, CANMET initiated a major research program to develop an engineering data base on the long-term effectiveness of supplementary cementing materials (SCMs) in reducing expansion and cracking in concrete due to AAR. 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 eighteen partners from Canada, U.S.A., Japan, Australia, and Korea (Table 1-1).

In this study, a number of reactive aggregates were selected to be tested in control concrete and mortar mixtures, and in mixtures incorporating various types and proportions of SCMs. From each of these mixtures, specimens of various types and sizes were cast and cured. Subsequently, they were subjected to accelerated test conditions in the laboratory and to natural environmental conditions to monitor the development of expansion and cracking due to ASR.

The main objective of the project is to develop an engineering data base on the long-term effectiveness of SCMs in controlling expansion and cracking of concrete due to alkali-silica reaction (ASR).

Table 1-1
1998 Project Advisory Committee of the CANMET/Industry Research Consortium on Alkali-Aggregate Reaction

Chairman: Dr. B. Fournier, CANMET

Representatives of the following industrial partners:
- Canadian Electrical Association, Montreal, PQ, Canada
- Cement and Concrete Association of Australia, Sydney, Australia
- Chichibu Onada Cement Corp., Tokyo, Japan
- Electric Power Research Institute, Palo Alto, CA, U.S.A.
- Federal Highway Administration, Washington D.C., U.S.A.
- FMC Corporation (Lithium division), Bessemer City, NC, U.S.A.
- Hydro-Québec, Montreal, PQ, Canada
- Inland Cement Ltd., Calgary, AL, Canada
- Lafarge Canada Inc., Montreal, PQ, Canada
- Minnesota Department of Transportation, U.S.A.
- New Brunswick Department of Transportation, Fredericton, NB, Canada
- Norchem Concrete Products, New York, NY, U.S.A.
- Portland Cement Association, Skokie, IL, U.S.A.
- Produits Chimiques Handy Ltée (Les), Montreal, PQ, Canada
- Province of Alberta, Canada
- Quebec Department of Transportation, Quebec City, PQ, Canada
- Shaw Resources, Lantz, NS, Canada
- SsangYong Cement Industrial Co. Ltd., Seoul, Korea
- St. Lawrence Cement, Montreal, PQ, Canada

Project Leader (CANMET): Dr. Benoit Fournier

Project consultants: Dr. Patrick E. Grattan-Bellew, NRC, Ottawa
Dr. Marc-André Bérubé, Laval University, Quebec City

2
DESCRIPTION OF THE STUDY

Scope

In this study, moderate and highly-reactive aggregates from different sources in Canada and the USA were selected to be tested. These were used in concrete mixtures made with high- and low-alkali ASTM Type I portland cements, and in mixtures incorporating various types of SCMs. Table 2-1 gives the basic concrete mixture proportioning matrix designed for the program. The SCMs consisted of four ASTM Class F fly ashes, one silica fume, and one granulated blast-furnace slag.

From each of the mixtures made in this study, cylinders, prisms, beams and slabs were cast and subjected to accelerated test conditions in the laboratory and natural environmental conditions at the CANMET outdoor exposure site in Ottawa, Canada. A number of parameters, such as the development of compressive strength and expansion and cracking due to ASR, are being monitored over a minimum of three years on laboratory specimens, and ten years on the field specimens. The various combinations were tested in both the Concrete Prism Test (CSA A23.2-14A [2], ASTM C1293 [3]) and the Accelerated Mortar Bar Test (CSA A23.2-25A [4], ASTM C 1260 [5]).

Materials

Aggregates

Three moderately-reactive and five highly-reactive aggregates were used in this study (Table 2-2). The fine aggregate used is non-reactive and derived from granite.

Portland Cements

High- and low-alkali ASTM Type I portland cements from Canada were used as control cements in the program. The chemical analysis and physical properties of the cements are given in Table 2-3. The high-alkali cements C3 and C4 were from the same plant but sampled at a few years interval.

Supplementary Cementing Materials

The SCMs used in this program consisted of ASTM Type F fly ashes from Canada and USA, a silica fume from Canada, and a granulated blast-furnace slag from Canada. The physical properties and the chemical analysis of the SCMs used to date in the mixing program are given in Table 2-4.

Chemical Admixtures and Lithium-based Compounds

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 mixtures.

Mixture Proportions

Concrete Mixtures

The proportioning of the concrete mixtures made with the aggregates, cements and SCMs selected for this study is given in Tables 2-5 to 2-12. The nominal cementitious material 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 material content was 375 ± 10 kg/m^3. Effective water-to-cementitious materials ratios ranging from 0.37 to 0.42 were obtained for all mixtures with the exception of the HVFA mixtures for which this value was 0.32 ± 0.01.

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

For a selected number of mixtures, reagent grade NaOH pellets were added to the mixture water in order to increase the total alkali content corresponding to the cement part of the concrete system to 1.25% Na_2O equivalent. Table 2-1 gives the corresponding total alkali content of the different concrete mixtures. All the concrete mixtures were air-entrained with the target air content of 6 ± 1%. The dosage of the superplasticizer in the silica fume and HVFA concrete mixtures was adjusted to obtain proper workability.

Mortar Mixtures

Mortar bars, made with the various combinations listed in Table 2-1, were also subjected to the CSA A23.2-25A (ASTM C 1260) Accelerated Mortar Bar Test. The fly ashes, slag and silica fume were used as separate ingredients in the mortar mixtures, i.e. as replacement, by mass, of the high-alkali cement. The water-to-cementitious materials ratio was kept constant at 0.50.

Table 2-1
Matrix of Concrete Mixtures Made in the Project: Highly-Reactive Aggregates

Aggregate (Cement and SCMs used)	Cementitious Materials Content (kg/m³)*	Alkali Content of the Mixture**	Low-Alkali Cement (C1) (Table 2-3)	High-Alkali Cements (C3, C4) (Table 2-3)	Fly Ash (FA1, FA2, FA3 & FA6) (Table 2-4)			Slag (Sg1 - Table 2-4)			Silica Fume (SF1 - Table 2-4)		
					20%	**30%**	**56%**	**35%**	**50%**	**65%**	**7.5%**	**10%**	**12.5%**
Po	420	-	M70	M62							M67		
(C1, C3, FA1, SF1)	420	+		M63		M71					M68	M69	
Sp	420	-	M26	M34	M57	M41		M30	M37	M46	M64	M65	M58
(C1, C3, FA2	420	+		M25		M42			M38			M66	
Sg1, SF1)	420	++				M44			M45				
Con	420, 375 (HVFA)	-	M87	M85	M88	M90	M92				M76	M77	
(C1, C4, FA1)	420, 375 (HVFA)	+		M86	M89	M91	M93						
	420	+++				M99							
Sl (C1, C3,	420, 375 (HVFA)	-	M1	M2	M19	M21	M23				M4	M5	M8
FA1, SF1)	420, 375 (HVFA)	+		M3	M20	M22	M24				M6	M7	M9
NM	420	-		M111									
(C4, FA6)	420	+			M160	M161							
Nominal	420, 375 (HVFA)	-	1.68	3.78	3.02	2.65	1.49	2.46	1.89	1.32	3.50	3.40	3.31
Alkali content	420, 375 (HVFA)	+	---	5.25	4.20	3.68	2.06	3.41	2.63	1.84	4.86	4.73	4.59
(kg/m³) ***	420	++				4.12			3.36				
	420	+++				5.25							

Aggregate (Cement and SCMs used)	Cementitious Materials Content (kg/m^3)*	Alkali Content of the Mixture**	Low-Alkali Cement (C1) (Table 2-3)	High-Alkali Cements (C3, C4) (Table 2-3)	Fly Ash (FA1, FA2, FA3 & FA6) (Table 2-4)			Slag (Sg1 - Table 2-4)			Silica Fume (SF1 - Table 2-4)		
					20%	**30%**	**56%**	**35%**	**50%**	**65%**	**7.5%**	**10%**	**12.5%**
Su	420, 375 (HVFA)	-	M10	M11	M35	M39	M47	M29	M27	M31	M12	M13	M16
(C1, C3, FA2	420, 375 (HVFA)	+		M18	M36	M40	M48	M33	M28	M32	M14	M15	M17
Sg1, SF1)	420	++				M43			M50				
Al	420	-	M84	M78	M94	M96					M80	M82	
(C1, C3, FA3, SF1)	420	+		M79	M95	M97					M81	M83	
	420	+++				M98							
Wy	420	-											
(C4, FA6)	420	+		M168	M169	M170							
Nominal	420, 375 (HVFA)	-	1.68	3.78	3.02	2.65	1.49	2.46	1.89	1.32	3.50	3.40	3.31
Alkali content	420, 375 (HVFA)	+	---	5.25	4.20	3.68	2.06	3.41	2.63	1.84	4.86	4.73	4.59
(kg/m^3) ***	420	++				4.12			3.36				
	420	+++				5.25							

* The nominal cementitious materials content for all mixtures was 420 ± 10 kg/m^3, except for the high-volume fly ash concretes for which it was 375 ± 10 kg/m^3.

** The "-" corresponds to concrete mixtures without added alkalies. The "+, ++, +++" correspond to concrete mixtures where NaOH pellets were added to the mixture water to raise the total alkali content of the mixture for acceleration purposes.

*** Calculated total alkali content of the mixture, expressed as Na_2O equivalent, but excluding the potential contribution by the SCMs.

Table 2-2
Coarse and Fine Aggregates Used in the Study

Aggregate	Location	Type	Rock Type	Expansion (%) AMBT *	Expansion (%) CPT**
				14 days	at 1 year
Su	Ontario (Canada)	Gravel	Sandstone, quartzwacke, arkose greywacke and argillite	0.278	0.075
Al	Alberta (Canada)	Gravel	Sandstone, limestone, quartzite and fine-grained volcanics	0.360	0.090
Wy	Wyoming (USA)	Gravel	Not Available	0.231	0.090
Po	Quebec (Canada)	Quarry	Siliceous sandstone	0.093	0.130
Sp	Ontario (Canada)	Quarry	Siliceous limestone and traces of chert	0.391	0.184
Con	Nova Scotia (Canada)	Quarry	Metagreywacke	0.419	0.196
Sl	New Brunswick (Canada)	Quarry	Greywacke	0.463	0.217
NM	New Mexico U.S.A.	Gravel	Mixed volcanics	0.854	0.212
Fine aggregate	Canada	Natural sand	Derived from granite	0.032	0.001

* Expansion (%) of mortar bars obtained after 14 days of immersion in a 1N NaOH solution at 80°C in the Accelerated Mortar Bar Method (CSA A23.2-25A, ASTM C 1260)

** Expansion of concrete prisms obtained after 1 year at 38°C and R.H. > 95% in the Concrete Prism Test (CSA A23.2-14A, ASTM C 1293). All mixtures of this series were air-entrained; they were also made with added alkalies, as per the CSA and ASTM recommendations, with the exceptions of the mixture made with aggregate NM,which was made without added alkalies.

Table 2-3
Physical Properties and Chemical Analysis of the Cements

Materials	Low-Alkali	High-Alkali	
Characteristics	**C1**	**C3**	**C4**
Physical Tests			
Fineness • passing 45 μm, %	93.1	90.8	93.5
• Blaine, m^2/kg	410	399	400
Specific Gravity	3.14	3.11	3.06
Compressive strength, MPa			
• 3 days	26.2	25.9	26.8
• 7 days	33.8	33.1	31.0
• 28 days	47.3	41.5	39.1
Chemical Analysis			
Silicon dioxide (SiO_2), %	21.15	20.15	20.42
Calcium oxide (CaO), %	60.35	61.72	62.39
Aluminum oxide (Al_2O_3), %	4.00	5.52	5.08
Ferric oxide (Fe_2O_3), %	5.39	2.59	2.37
Magnesium oxide (MgO), %	3.40	2.19	2.55
Sulphur oxide (SO_3), %	2.46	4.98	3.11
Strontium oxide (SrO), %	0.06	n.a.	0.19
Loss on ignition, %	2.25	1.54	2.50
Sodium oxide (Na_2O), %	0.13	0.18	0.22
Potassium oxide (K_2O), %	0.41	1.09	1.03
Total alkalies, (Na_2O equiv.), %	0.40	0.90	0.90
Bogue Potential Coumpound Composition			
C_3S	43	43	52
C_2S	28	25	19
C_3A	2	10	10
C_4AF	16	8	7

Table 2-4
Physical Properties and Chemical Analysis of the Supplementary Cementing Materials

Materials Characteristics		ASTM Class F Fly Ashes				Slag	Silica Fume
		FA 1	FA 2	FA 3	FA 6	Sg 1	SF 1
Physical Tests							
Fineness	• passing 45 μm, %	78.2	71.5	82.9	74.5	98.96	97.48
	• Blaine, m^2/kg	262	273	245	n.a.	436	...
Specific Gravity		2.46	2.41	2.05	2.28	2.92	2.15
Strength Activity Index, % *							
	• 7 days	80.6	84.6	77.8	89.2	74.9	105.9
	• 28 days	90.0	93.9	94.7	95.7	101.7	118.7
Chemical Analysis							
Silicon dioxide (SiO_2), %		41.72	50.16	55.62	59.15	35.7	93.60
Calcium oxide (CaO), %		2.06	2.39	9.07	7.45	34.3	0.50
Aluminum oxide (Al_2O_3), %		19.7	26.84	20.33	19.13	9.60	0.06
Ferric oxide (Fe_2O_3), %		26.03	12.75	4.08	5.27	0.55	0.45
Magnesium oxide (MgO), %		0.87	0.89	0.94	2.47	14.1	0.67
Sulphur oxide (SO_3), %		1.08	0.78	3.43	0.18	3.69	0.32
Strontium oxide (SrO), %		0.16	n.a.	0.30	0.23	0.04	n.a.
Loss on ignition, %		3.38	2.80	0.50	0.18	1.59	2.26
Sodium oxide (Na_2O), %		0.79	0.26	4.22	2.50	0.53	0.16
Potassium oxide (K_2O), %		2.12	2.24	1.85	1.06	0.42	0.85
Sodium oxide equivalent, %		2.19	1.73	5.44	3.20	0.81	0.72

* The strength activity index was determined with the high-alkali control cement C3 (Table 2-3).

Table 2-5
Proportioning of Concrete Mixtures Incorporating Moderately-Reactive Aggregate Su

Concrete Mixture Designation		Cementitious Materials Content, kg/m^3							Aggregates (SSD)		Chemical Admixtures		Alkali content	
		Cement		Fly Ash	Slag	Silica Fume		W	Coarse,	Fine,	A.E.A.,	S.P.,	NaOH added	Na_2O eq.
		C1	C3	FA2	Sg1	SF1	Total	C + SCM	kg/m^3	kg/m^3	mL/m^3	L/m^3	kg/m^3	kg/m^3
Su L	M10	424	...	....	....	....	424	0.42	1026	683	225	....	0.00	1.70
Su	M11	...	422	....	....	....	422	0.42	1023	681	120	....	0.00	3.80
Su+	M18	...	419	....	....	....	419	0.42	1016	677	120	....	1.90	5.24
Su FA 20	M35	...	341	85	....	....	426	0.39	1029	687	236	....	0.00	3.07
Su FA 20+	M36	...	339	85	....	....	424	0.39	1022	682	213	....	1.54	4.24
Su FA 30	M39	...	299	128	....	....	427	0.38	1032	689	288	....	0.00	2.69
Su FA 30+	M40	...	297	127	....	....	424	0.38	1025	684	368	....	1.34	3.71
Su FA 30++	M43	...	297	127	....	....	424	0.38	1025	684	327	....	1.92	4.16
Su FA 56	M47	...	161	223	....	....	384	0.32	1132	755	3845	4.5	0.00	1.45
Su FA 56+	M48	...	158	219	....	....	377	0.32	1112	742	2197	3.7	0.71	1.97
Su Sg 35	M29	...	280	....	151	....	431	0.41	1037	693	172	....	0.00	2.52
Sp Sg 35+	M33	...	276	....	148	....	424	0.40	1028	686	188	....	1.24	3.44
Su Sg 50	M27	...	210	....	210	....	420	0.41	1011	676	200	....	0.00	1.89
Su Sg 50+	M28	...	212	....	212	....	424	0.41	1017	680	204	....	0.96	2.65
Su Sg 50++	M50	...	212	....	212	....	424	0.41	1017	680	207	....	1.91	3.39
Su Sg 65	M31	...	149	....	276	....	425	0.40	1028	687	738	....	0.00	1.34
Su Sg 65+	M32	...	149	....	276	....	425	0.40	1028	689	793	....	0.68	1.87
Su SF 7.5	M12	...	390	....	....	32	422	0.42	1014	676	153	1.6	0.00	3.51
Su SF 7.5+	M14	...	392	....	....	32	424	0.42	1020	679	145	1.9	1.78	4.91
Su SF 10	M13	...	383	....	....	43	426	0.42	1020	679	162	2.4	0.00	3.45
Su SF 10+	M15	...	385	....	....	43	428	0.42	1026	682	168	2.3	1.75	4.82
Su SF 12.5	M16	...	373	....	....	53	426	0.42	1020	679	174	2.9	0.00	3.36
Su SF 12.5+	M17	...	372	....	....	53	425	0.42	1019	678	183	2.9	1.67	4.64

Table 2-6
Proportioning of Concrete Mixtures Incorporating Moderately-Reactive Aggregate Al

Concrete Mixture Designation		Cementitious Materials Content, kg/m³						Aggregates (SSD)		Chemical Admixtures		Alkali Content	
		Cement		Fly Ash	Silica Fume		W	Coarse,	Fine,	A.E.A.,	S.P.,	NaOH added	Na_2O eq.
		C1	C3	FA3	SF1	Total	C + SCM	kg/m³	kg/m³	mL/m³	L/m³	kg/m³	kg/m³
Al L	M84	438	...	....	....	438	0.39	1048	698	384	....	0.00	1.75
Al	M78	...	436	....	....	436	0.37	1045	696	257	....	0.00	3.92
Al+	M79	...	433	....	....	433	0.37	1037	691	206	....	1.96	5.42
Al FA 20	M94	...	346	87	....	433	0.39	1012	675	223	....	0.00	3.11
Al FA 20+	M95	...	346	87	....	433	0.38	1013	675	251	....	1.60	4.35
Al FA 30	M96	...	303	130	....	433	0.36	1018	681	237	....	0.00	2.73
Al FA 30+	M97	...	303	130	....	433	0.36	1018	681	270	....	1.37	3.79
Al FA 30+++	M98	...	304	130	....	434	0.36	1023	698	229	....	3.47	5.42
Al SF 7.5	M80	...	407	....	33	440	0.41	1031	687	151	0.4	0.00	3.66
Al SF 7.5+	M81	...	404	....	33	437	0.41	1024	682	159	0.6	1.83	5.05
AL SF 10	M82	...	387	....	43	430	0.41	1005	670	172	0.8	0.00	3.48
Al SF 10+	M83	...	389	....	43	432	0.41	1011	674	211	0.5	1.77	4.87

Table 2-7
Proportioning of Concrete Mixtures Incorporating Moderately-Reactive Aggregate Wy

Concrete Mixture Designation		Cementitious Materials Content, kg/m³						Aggregates (SSD)		Chemical Admixtures		Alkali Content	
		Cement		Fly Ash	Silica Fume		W	Coarse,	Fine,	A.E.A.,	S.P.,	NaOH added	Na_2O eq.
		C1	C4	FA6	SF1	Total	C + SCM	kg/m³	kg/m³	mL/m³	L/m³	kg/m³	kg/m³
Wy+	M168	...	428	....	....	428	0.38	1013	675	146	....	1.94	5.35
Wy FA 20+	M169	...	338	84	....	422	0.37	1004	669	214	....	1.53	4.20
Wy FA 30+	M170	...	296	127	....	423	0.36	1003	669	220	....	1.34	3.70

Table 2-8
Proportioning of Concrete Mixtures Incorporating Highly-Reactive Aggregate Po

Concrete Mixture Designation		Cementitious Materials Content, kg/m^3					W / (C + SCM)	Aggregates (SSD)		Chemical Admixtures		Alkali Content	
		Cement		Fly Ash	Silica Fume			Coarse,	Fine,	A.E.A.,	S.P.,	NaOH added	Na_2O eq.
		C1	C3	FA1	SF1	Total		kg/m^3	kg/m^3	mL/m^3	L/m^3	kg/m^3	kg/m^3
Po L	M70	425	...	....	....	425	0.40	995	664	493	....	0.00	1.70
Po	M62	...	428	....	....	428	0.40	1000	667	198	....	0.00	3.85
Po+	M63	...	431	....	....	431	0.40	1007	672	205	....	1.94	5.38
Po FA 30+	M71	...	298	128	....	426	0.38	999	665	274	....	1.35	3.73
Po SF 7.5	M67	...	394	....	32	426	0.41	982	655	383	2.5	0.00	3.55
Po SF 7.5+	M68	...	396	....	32	428	0.41	988	659	342	2.2	1.79	4.95
Po SF 10+	M69	...	383	....	43	426	0.41	981	654	548	2.7	1.74	4.79

Table 2-9
Proportioning of Concrete Mixtures Incorporating Highly-Reactive Aggregate Sp

Concrete Mixture Designation		Cementitious Materials Content, kg/m^3 Cement C1	C3	Fly Ash FA2	Slag Sg1	Silica Fume SF1	Total	W / C + SCM	Aggregates (SSD) Coarse, kg/m^3	Fine, kg/m^3	Chemical Admixtures A.E.A., mL/m^3	S.P., L/m^3	Alkali Content NaOH added kg/m^3	Na_2O eq. kg/m^3
Sp L	M26	417	...	....	....	....	417	0.42	1003	673	232	....	0.00	1.67
Sp	M34	...	427	....	....	....	427	0.41	1033	690	181	....	0.00	3.84
Sp+	M25	...	418	....	....	....	418	0.42	1003	670	119	....	1.89	5.23
Sp FA 20	M57	...	338	84	....	....	422	0.39	1016	677	326	....	0.00	3.04
Sp FA 30	M41	...	298	128	....	....	426	0.38	1023	683	351	....	0.00	2.68
Sp FA 30+	M42	...	296	127	....	....	423	0.38	1017	679	375	....	1.34	3.70
Sp FA 30++	M44	...	296	127	....	....	423	0.38	1016	678	375	....	1.95	4.17
Sp Sg 35	M30	...	277	....	149	....	426	0.40	1022	682	239	....	0.00	2.49
Sp Sg 50	M37	...	212	....	212	....	424	0.40	1021	680	587	....	0.00	1.91
Sp Sg 50+	M38	...	212	....	212	....	424	0.40	1020	680	328	....	0.96	2.65
Sp Sg 50++	M45	...	211	....	211	....	422	0.40	1013	676	637	....	1.90	3.37
Sp Sg 65	M46	...	149	....	276	....	425	0.41	1019	678	1131	....	0.00	1.34
Sp SF 7.5	M64	...	391	....	....	32	423	0.41	1010	674	326	1.9	0.00	3.52
Sp SF 10	M65	...	379	....	....	42	421	0.41	1004	669	435	2.6	0.00	3.41
Sp SF 10+	M66	...	378	....	....	42	420	0.41	1003	668	358	2.5	1.72	4.73
Sp SF 12.5	M58	...	371	....	....	53	424	0.41	1009	673	355	2.7	0.00	3.34

Table 2-10
Proportioning of Concrete Mixtures Incorporating Highly-Reactive Aggregate Con

Concrete Mixture Designation		Cementitious Materials Content, kg/m^3						Aggregates (SSD)		Chemical Admixtures		Alkali Content	
		Cement		Fly Ash	Silica Fume		W	Coarse,	Fine,	A.E.A.,	S.P.	NaOH added	Na_2O eq.
		C1	C4	FA1	SF1	Total	C + SCM	kg/m^3	kg/m^3	mL/m^3	L/m^3	kg/m^3	kg/m^3
Con L	M87	430	...	....	....	430	0.40	1041	694	277	....	0.00	1.72
Con	M85	...	427	....	....	427	0.40	1035	690	110	....	0.00	3.84
Con +	M86	...	427	....	....	427	0.40	1034	689	96	....	1.93	5.34
Con FA 20	M88	...	343	86	....	429	0.39	1036	691	97	....	0.00	3.09
Con FA 20+	M89	...	341	85	....	426	0.39	1029	686	82	....	1.54	4.26
Con FA 30	M90	...	304	130	....	434	0.38	1051	701	98	....	0.00	2.74
Con FA 30+	M91	...	304	130	....	434	0.38	1051	701	103	....	1.37	3.80
Con FA 30++	M99	...	299	128	....	427	0.38	1034	689	110	....	3.41	5.33
Con FA 56	M92	...	160	214	....	374	0.33	1138	759	410	4.3	0.00	1.44
Con FA 56+	M93	...	159	212	....	371	0.33	1131	754	229	4.7	0.71	1.98
Con SF 7.5	M76	...	402	....	33	435	0.41	1043	696	353	1.8	0.00	3.62
Con SF 10	M77	...	387	....	43	430	0.41	1030	687	440	2.7	0.00	3.48

Table 2-11
Proportioning of Concrete Mixtures Incorporating Highly-Reactive Aggregate SI

Concrete Mixture Designation		Cementitious Materials Content, kg/m^3					W / (C + SCM)	Aggregates (SSD)		Chemical Admixtures		Alkali Content	
		Cement		Fly Ash	Silica Fume			Coarse,	Fine,	A.E.A.,	S.P.,	NaOH added	Na_2O eq.
		C1	C3	FA1	SF1	Total		kg/m^3	kg/m^3	mL/m^3	L/m^3	kg/m^3	kg/m^3
SI L	M1	423	...	....	....	423	0.42	1021	683	233	....	0.00	1.69
SI	M2	...	423	....	....	423	0.42	1021	683	123	....	0.00	3.81
SI +	M3	...	425	....	....	425	0.42	1026	686	111	....	1.92	5.31
SI FA 20	M19	...	343	86	....	429	0.41	1032	689	171	....	0.00	3.09
SI FA 20+	M20	...	342	86	....	428	0.41	1032	689	160	....	1.58	4.30
SI FA 30	M21	...	303	130	....	433	0.39	1051	702	195	....	0.00	2.73
SI FA 30+	M22	...	299	128	....	427	0.39	1037	693	220	....	1.35	3.74
SI FA 56	M23	...	160	222	....	382	0.32	1140	762	334	4.9	0.00	1.44
SI FA 56+	M24	...	158	219	....	377	0.32	1126	753	688	4.0	0.71	1.97
SI SF 7.5	M4	...	393	....	32	425	0.42	1019	681	165	1.8	0.00	3.54
SI SF 7.5+	M6	...	390	....	32	422	0.42	1012	676	137	2.2	1.77	4.88
SI SF 10	M5	...	381	....	42	423	0.42	1011	676	173	2.7	0.00	3.43
SI SF 10+	M7	...	381	....	42	423	0.42	1011	676	142	3	1.73	4.77
SI SF 12.5	M8	...	371	....	53	424	0.42	1011	676	173	3.3	0.00	3.34
SI SF 12.5+	M9	...	373	....	53	426	0.42	1017	679	163	3.3	1.68	4.66

Table 2-12
Proportioning of Concrete Mixtures Incorporating Highly-Reactive Aggregate NM

Concrete Mixture Designation		Cementitious Materials Content, kg/m^3					W / C + SCM	Aggregates (SSD)		Chemical Admixtures		Alkali Content	
		Cement		Fly Ash	Silica			Coarse,	Fine,	A.E.A.,	S.P.	NaOH added,	Na_2O eq.
		C1	C4	FA 6	Fume	Total		kg/m^3	kg/m^3	mL/m^3	L/m^3	kg/m^3	kg/m^3
NM	M111	….	431	....	....	431	0.40	1028	685	69	....	0.0	3.88
NM FA 20+	M160	….	337	84	....	421	0.38	1018	680	190	....	1.53	4.22
NM FA 30+	M161	….	295	126	....	421	0.37	1020	681	157	....	1.33	3.69

Properties of Fresh and Hardened Concrete

The properties of the freshly mixed concrete are given in Tables 2-13 to 2-20. The target of 6 ± 1% for the air content in fresh concrete was generally achieved. The 7-, 28-, 91-, 365-, and 730-day compressive strengths obtained for the different concrete mixtures are also given in the above Tables.

Laboratory and Field Testing of Specimens

Laboratory Test Specimens

Concrete specimens for compressive strength determination

Concrete cylinders, 100 by 200 mm in size, were cast from each of the concrete mixtures made in this study. The specimens to be tested at the ages of 7, 28, and 91 days were stored in the moist curing room (temperature 23 ± 1.5°C and relative humidity > 95%), while those to be tested at later ages, i.e. one year and two years, were placed in a lime-saturated water bath at 23 ± 2°C for long-term storage.

Concrete specimens for AAR expansion testing

Concrete prisms, 75 by 75 by 300 mm in size, were cast from each mixture; the test prisms, in sets of three, were stored at 38°C and at relative humidity > 95% (Fig. 2-1Aand 2-1B). The length change of the concrete prisms was monitored at ages of 1, 2, 4, 8, 13, 18 26, 39, 52 weeks, and thereafter at every three months for a minimum of three years (Fig. 2-2).

Mortar specimens for AAR expansion testing

According to CSA A23.2-25A test procedure, three mortar bars, 25 by 25 by 225-mm in size, were cast from each mortar mixture made in this study. Immediately after casting, the moulds were covered with a plastic sheet and placed in a moist-curing room at 23°C for a pezriod of 24 ± 2 hours. The bars were then demoulded and placed in a plastic Rubbermaid container (6 bars per container) filled with tap water at room temperature, and the containers were placed in an oven maintained at 80 ± 2°C for a period of 24 hours.

After the 24-hour pre-curing period in tap water at 80 ± 2°C, the length of the mortar bars was measured (initial reading, i.e. L0), and immediately the bars were transferred into plastic storage containers (three bars per container) filled with a 1N NaOH solution at 80°C. The containers were then returned to the oven at 80°C for a period of 28 days.

The length change of the mortar bars, in the 1N NaOH solution at 80°C, was measured at least five times during the first 14 days of immersion and every week afterwards, up to a maximum of four weeks.

A **B**

Figure 2-1
(A) Concrete prisms stored in plastic sleeves and placed in vertical position inside a 25-L plasticpail for long-term storage at 38°C.
(B) Temperature-controlled room at 38°C used for the Concrete Prism Test.

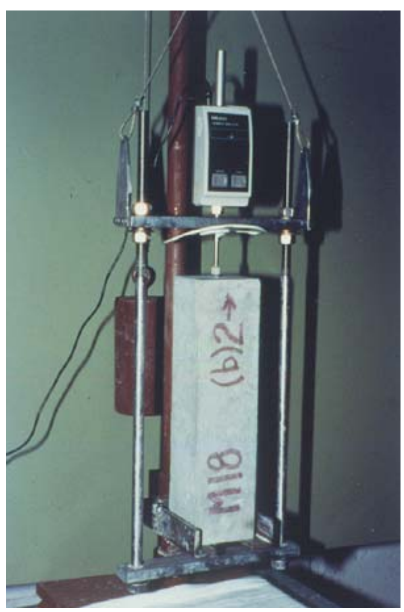

Figure 2-2
Measuring device used to monitor expansion of test pris

Concrete 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 concrete mixtures made in this study. For monitoring the length changes, eight stainless steel threaded studs, 9 mm in diameter by 75 mm long, were partially embedded in the concrete beams, four in the case of concrete slabs (Fig. 2-3A to 2-3D)

A

B

C

D

Figure 2-3
(A) Concrete beams exposed outdoors. Four stainless steel measuring studs appear on the topsurface of each beam, and two on each side.
(B) The slabs are placed directly on the gravel pad. Only the top surface of the slab is directly exposed to the atmosphere.
(C) Longitudinal measurement on the top of concrete beams
(D) Measurement on concrete slabs

The blocks and slabs were placed on a 0.3m thick gravel pad of well-compacted 0-25 mm crushed limestone material (Fig. 2-4A); the first beam (Beam A) is placed directly on the gravel while the second one (Beam B) is placed above ground, sitting on two 200 mm in diameter by

0.40 m long concrete cylinders cut lengthwise (Fig. 2-4A). The concrete slabs were placed directly on the compacted gravel pad, with granular material placed around and between each slab so that only the top surface of the slab is exposed (Fig. 2-3B and 2-4B).

A **B**

Figure 2-4
(A) Concrete beams are placed either directly on the ground or above ground level, sitting on two 200-mm diameter by 400-mm long concrete cylinders cut lengthwise
(B) General view of a section of CANMET outdoor exposure site in Ottawa

Table 2-13
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Moderately-Reactive Aggregate Su

Mixture Designation		Cementitious Materials Content, kg/m³					W / C + SCM	Slump,	Air,	Unit Weight,	Compressive Strength (Mpa), Days				
		Cement	Fly Ash	Slag	Silica Fume	Total		mm	%	kg/m³	7	28	91	365	730
Su L	M10	424	....	....	....	424	0.42	145	6.4	2310	....	40.0	45.3	50.3	53.1
Su	M11	422	....	....	....	422	0.42	150	6.6	2303	....	33.1	38.5	44.7	46.3
Su+	M18	419	....	....	....	419	0.42	160	7.1	2288	....	....	39.1	43.1	44.8
Su FA 20	M35	341	85	....	....	426	0.39	140	6.8	2310	22.0	30.5	37.7	43.6	46.5
Su FA 20+	M36	339	85	....	....	424	0.39	165	6.4	2296	22.5	31.7	38.8	42.8	44.2
Su FA 30	M39	299	128	....	....	427	0.38	105	5.9	2310	20.4	31.4	36.9	43.2	43.0
Su FA 30+	M40	297	127	....	....	424	0.38	95	6.2	2296	19.4	27.0	32.8	35.6	36.2
Su FA 30++	M43	297	127	....	....	424	0.38	90	6.4	2296	19.1	26.5	33.2	34.7	34.5
Su FA 56	M47	161	223	....	....	384	0.32	165	4.3	2394	20.0	29.9	38.2	49.4	54.9
Su FA 56+	M48	158	219	....	....	377	0.32	200	5.3	2352	19.3	29.8	39.7	51.4	58.2
Su Sg 35	M29	280	....	151	....	431	0.41	145	6.2	2338	25.9	33.4	38.0	45.4	45.7
Su Sg 35+	M33	276	....	148	....	424	0.40	150	6.0	2310	24.5	32.2	34.0	39.1	42.2
Su Sg 50	M27	210	....	210	....	420	0.41	115	6.7	2281	22.7	29.2	32.0	36.4	37.7
Su Sg 50+	M28	212	....	212	....	424	0.41	160	6.6	2296	21.4	28.1	31.0	34.7	38.0
Su Sg 50++	M50	212	....	212	....	424	0.41	165	5.9	2296	19.9	30.3	39.5	46.1	50.4
Su Sg 65	M31	149	....	276	....	425	0.40	65	6.2	2310	19.4	28.4	33.9	34.0	37.8
Su Sg 65+	M32	149	....	276	....	425	0.40	80	6.9	2310	21.4	29.8	35.5	37.8	38.0
Su SF 7.5	M12	390	....	....	32	422	0.42	140	6.9	2288	....	43.7	44.9	46.3	49.1
Su SF 7.5+	M14	392	....	....	32	424	0.42	140	6.0	2303	....	42.2	45.0	47.7	47.1
Su SF 10	M13	383	....	....	43	426	0.42	135	6.0	2303	....	45.1	46.1	47.3	48.1
Su SF 10+	M15	385	....	....	43	428	0.42	125	5.7	2317	....	42.8	44.7	46.5	47.2
Su SF 12.5	M16	373	....	....	53	426	0.42	140	5.8	2303	....	46.5	46.4	48.7	50.2
Su SF 12.5+	M17	372	....	....	53	425	0.42	160	5.9	2303	....	45.5	45.0	47.8	49.0

Table 2-14
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Moderately-Reactive Aggregate A

Mixture Designation		Cementitious Materials Content, kg/m³ Cement	Fly Ash	Silica Fume	Total	W / C + SCM	Slump, mm	Air, %	Unit Weight, kg/m³	Compressive Strength (MPa), Days 7	28	91	365	730
Al L	M84	438	....	....	438	0.39	75	6.8	2352	33.1	39.8	45.6	52.3	54.0
Al	M78	436	....	....	436	0.37	75	6.7	2338	27.3	35.5	44.7	45.7	49.9
Al+	M79	433	....	....	433	0.37	95	6.9	2324	28.0	36.8	41.5	46.3	46.4
Al FA 20	M94	346	87	....	433	0.39	150	6.2	2288	22.3	29.4	38.6	44.2	46.7
Al FA 20+	M95	346	87	....	433	0.38	140	6.3	2288	20.4	29.8	31.4	42.0	44.9
Al FA 30	M96	303	130	....	433	0.36	110	n.a.	2288	22.2	27.4	36.6	45.1	48.2
Al FA 30+	M97	303	130	....	433	0.36	75	6.3	2288	21.0	30.0	35.4	41.2	41.1
Al FA 30++	M98	304	130	....	434	0.36	120	5.4	2317	22.0	34.1	36.8	40.6	46.0
Al SF 7.5	M80	407	...	33	440	0.41	75	6.0	2338	36.0	43.1	46.9	47.0	47.3
Al SF 7.5+	M81	404	...	33	437	0.41	95	6.2	2324	30.8	40.9	42.4	43.1	43.6
Al SF 10	M82	387	....	43	430	0.41	75	6.4	2281	33.9	37.2	38.7	41.2	42.5
Al SF 10+	M83	389	....	43	432	0.41	75	6.3	2296	31.4	39.4	40.4	41.7	46.8

Table 2-15
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Moderately-Reactive Aggregate Wy

Mixture Designation		Cementitious Materials Content, kg/m³ Cement	Fly Ash	Silica Fume	Total	W / C + SCM	Slump, mm	Air, %	Unit Weight, kg/m³	Compressive Strength (Mpa), Days 7	28	91	365	730
Wy+	M168	428	....	....	428	0.38	75	7.0	2279	22.9	30.8	32.9	37.4	....
Wy FA 20+	M169	338	84	....	422	0.37	95	7.5	2253	20.4	28.8	31.0	35.1	....
Wy FA 30+	M170	296	127	....	423	0.36	120	7.0	2246	21.3	32.1	32.5	39.6	....

Table 2-16
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Highly-Reactive Aggregate Po

Mixture		Cementitious Materials Content, kg/m³				W / C + SCM	Slump,,	Air,	Unit Weight,	Compressive Strength (MPa), Days				
Designation		Cement	Fly Ash	Silica Fume	Total		mm	%	kg/m³	7	28	91	365	730
Po L	M70	425	....	....	425	0.40	90	6.7	2253	28.1	37.5	43.0	47.4	47.8
Po	M62	428	....	....	428	0.40	140	6.6	2267	28.9	35.8	41.5	47.6	46.3
Po+	M63	431	....	....	431	0.40	110	6.0	2281	31.7	36.6	43.0	45.5	49.8
Po FA 30+	M71	298	128	....	426	0.38	150	6.8	2253	17.8	28.6	34.3	42.3	42.9
Po SF 7.5	M67	394	....	32	426	0.41	125	6.9	2239	33.5	43.6	46.6	49.5	49.6
Po SF 7.5+	M68	396	....	32	428	0.41	140	6.2	2253	32.4	40.9	43.9	46.6	48.7
Po SF 10+	M69	383	....	43	426	0.41	140	6.4	2239	34.9	45.7	47.6	48.2	50.0

Table 2-17
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Highly-Reactive Aggregate Sp

Mixture Designation		Cementitious Materials Content, kg/m^3					W / C + SCM	Slump, mm	Air, %	Unit Weight, kg/m^3	Compressive Strength (MPa), Days				
		Cement	Fly Ash	Slag	Silica Fume	Total					7	28	91	365	730
Sp L	M26	417	....	....	....	417	0.42	125	5.3	2267	33.2	42.8	51.2	56.6	58.8
Sp	M34	427	....	....	....	427	0.41	140	6.0	2324	30.5	37.4	42.4	45.9	39.6
Sp+	M25	418	....	....	....	418	0.42	120	5.5	2267	31.1	35.7	44.1	42.5	37.3
Sp FA 20	M57	338	84	....	....	422	0.39	100	6.2	2281	23.9	33.4	43.2	51.4	52.9
Sp FA 30	M41	298	128	....	....	426	0.38	100	6.2	2296	22.6	34.0	40.6	47.4	47.7
Sp FA 30+	M42	296	127	....	....	423	0.38	100	6.7	2281	21.0	29.6	35.8	42.3	43.7
Sp FA 30++	M44	296	127	....	....	423	0.38	100	6.4	2281	20.1	27.4	32.4	37.8	38.8
Sp Sg 35	M30	277	....	149	....	426	0.40	115	6.8	2303	27.9	35.6	40.3	47.6	48.4
Sp Sg 50	M37	212	....	212	....	424	0.40	75	6.4	2296	23.0	30.4	34.0	40.1	....
Sp Sg 50+	M38	212	....	212	....	424	0.40	145	6.0	2296	22.4	30.5	34.4	37.0	....
Sp Sg 50++	M45	211	....	211	....	422	0.40	75	6.2	2281	21.6	27.1	31.2	38.6	40.0
Sp Sg 65	M46	149	....	276	....	425	0.41	90	5.5	2296	20.2	28.1	34.6	39.0	44.0
Sp SF 7.5	M64	391	....	....	32	423	0.41	90	6.0	2281	33.5	40.5	42.7	44.8	47.2
Sp SF 10	M65	379	....	....	42	421	0.41	100	6.4	2267	32.1	39.3	40.2	43.3	43.0
Sp SF 10+	M66	378	....	....	42	420	0.41	115	6.6	2267	31.8	38.3	40.3	43.0	42.5
Sp SF 12.5	M58	371	....	....	53	424	0.41	120	6.1	2281	33.0	44.2	46.1	49.6	51.0

Table 2-18
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Highly-Reactive Aggregate Con

Mixture		Cementitious Materials Content, kg/m³				W	Slump,	Air,	Unit Weight,	Compressive Strength (MPa), Days				
Designation		Cement	Fly Ash	Silica Fume	Total	C + SCM	mm	%	kg/m³	7	28	91	365	730
Con L	M87	430	....	....	430	0.40	75	6.2	2338	32.7	41.2	47.5	53.1	54.7
Con	M85	427	....	....	427	0.40	95	6.9	2324	26.6	33.8	38.2	44.5	41.9
Con+	M86	427	....	....	427	0.40	95	7.0	2324	22.9	28.8	35.5	38.1	36.8
Con FA 20	M88	343	86	....	429	0.39	100	6.8	2324	22.3	31.7	38.9	43.0	46.2
Con FA 20+	M89	341	85	....	426	0.39	125	6.8	2310	20.1	26.9	35.9	40.7	40.2
Con FA 30	M90	304	130	....	434	0.38	110	6.0	2352	25.2	34.1	40.3	50.3	51.3
Con FA 30+	M91	304	130	....	434	0.38	120	5.9	2352	21.3	30.7	35.8	44.4	45.5
Con FA 30+++	M99	299	128	....	427	0.38	140	6.5	2317	17.3	24.2	34.2	38.5	38.0
Con FA 56	M92	160	214	....	374	0.33	85	5.8	2394	....	31.7	41.5	49.9	52.6
Con FA 56+	M93	159	212	....	371	0.33	225	5.8	2380	....	36.0	45.8	54.1	58.9
Con SF 7.5	M76	402	....	32	435	0.41	110	6.2	2345	32.1	40.4	44.3	49.7	...
Con SF 10	M77	387	....	43	430	0.41	140	7.2	2317	34.5	43.3	45.0	50.2	...

Table 2-19
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Highly-Reactive Aggregate SI

Mixture		Cementitious Materials Content, kg/m^3				W	Slump,	Air,	Unit Weight,	Compressive Strength (MPa), Days				
Designation		Cement	Fly Ash	Silica Fume	Total	C + SCM	mm	%	kg/m^3	7	28	91	365	730
SI L	M1	423	....	....	423	0.42	90	6.9	2303	....	39.9	47.9	49.4	53.2
SI	M2	423	....	....	423	0.42	115	6.6	2303	....	37.6	44.1	48.5	53.0
SI +	M3	425	....	....	425	0.42	90	6.4	2317	....	36.0	41.8	44.5	38.5
SI FA 20	M19	343	86	....	429	0.41	115	5.4	2324	22.5	31.7	42.4	45.6	47.8
SI FA 20+	M20	342	86	....	428	0.41	150	5.7	2324	24.2	32.9	40.5	46.2	46.5
SI FA 30	M21	303	130	....	433	0.39	100	5.2	2352	21.2	31.1	41.6	46.6	45.9
SI FA 30+	M22	299	128	....	427	0.39	100	6.4	2324	19.5	29.1	37.0	41.3	40.9
SI FA 56	M23	160	222	....	382	0.32	140	5.2	2409	20.8	38.2	46.7	53.9	57.7
SI FA 56+	M24	158	219	....	377	0.32	135	6.2	2380	18.6	34.0	43.1	46.8	53.3
SI SF 7.5	M4	393	....	32	425	0.42	65	6.6	2303	....	42.3	44.2	47.1	48.6
SI SF 7.5+	M6	390	....	32	422	0.42	115	6.4	2288	....	47.7	50.7	52.7	51.9
SI SF 10	M5	381	....	42	423	0.42	110	7.1	2288	....	44.0	45.2	46.6	47.4
SI SF 10+	M7	381	....	42	423	0.42	115	6.3	2288	....	47.4	49.2	52.6	54.1
SI SF 12.5	M8	371	....	53	424	0.42	135	6.4	2288	....	44.3	44.4	46.8	48.2
SI SF 12.5+	M9	373	....	53	426	0.42	140	6.1	2303	....	42.6	43.0	45.0	46.7

Table 2-20
Properties of Fresh and Hardened Concrete Made From Mixtures Incorporating Highly-Reactive Aggregate NM

Mixture Designation		Cementitious Materials Content, kg/m^3			W/(C + SCM)	Slump, mm	Air, %	Unit Weight, kg/m^3	Compressive Strength (MPa), Days			
		Cement	Fly Ash	Total					7	28	91	365
NM	M111	431	....	431	0.40	80	6.0	2317	30.8	38.3	41.0	35.0
NM FA 20+	M160	337	84	421	0.38	80	6.6	2280	22.1	30.2	35.8	…
NM FA 30+	M161	295	126	421	0.37	105	6.7	2279	21.6	33.4	38.2	…

3
TEST RESULTS AND DISCUSSION

Compressive Strength

Control Concrete Mixtures

In general, control concrete mixtures incorporating the low-alkali cement exhibited higher compressive strengths than those made with the high-alkali cement. Slight to significant reductions in compressive strengths were observed with the addition of NaOH to the mixing water of concretes incorporating high-alkali cements.

Concrete Mixtures Incorporating SCMs

As expected, early-age compressive strengths of fly ash concretes were generally lower than that of control mixtures incorporating the high-alkali cement; this difference decreased with time. The compressive strengths of the high-volume fly ash (HVFA) concretes were higher than that of the corresponding control mixtures in general, except at 7 days. The difference in the compressive strengths of fly ash concretes with and without added alkalies was generally not significant at the 20% replacement level, and was generally within 2 MPa. Significant reductions in the compressive strengths, i.e 8 to 10 MPa, were noticed when large amounts of alkalies were added to concrete mixtures incorporating 30% fly ash.

The compressive strengths of the concretes incorporating 35% slag were similar to those of the concretes made with the high-alkali cement; however, the strengths of the 35% slag concretes were significantly higher than those of the mixtures incorporating 50 or 65% slag at a given age. The difference in the compressive strengths between the 35% and both the 50 and 65% slag mixtures was also found to stay the same, or decreased slightly with time, for a given aggregate. The addition of NaOH did not have a clear effect on the compressive strength of the slag concretes.

For a given aggregate, the compressive strengths of the silica fume concretes were generally similar to or slightly higher than those of the control concretes made with the high-alkali cement. Also, for a specific aggregate and a specific age, only small differences in the compressive strengths, within 2 to 3 MPa, were obtained between the concretes incorporating 7.5, 10 or 12.5% silica fume. The addition of the alkalies seems to have no significant effect on the compressive strength of most silica fume concretes.

Alkali-Aggregate Reactivity Testing in the Laboratory – Length Changes in Concrete Prisms

General Comments on Standard Concrete Prism Test Procedures

Evaluating the Potential Alkali-Reactivity of Aggregates

According to the Appendix B of CSA A23.1-00 [6] and the CSA Standard Practice A23.2-27A [7], an aggregate is to be considered potentially alkali-reactive if it produces an expansion > 0.04% after subjected to the A23.2-14A Concrete Prism Test for one year. A cement content of 420 kg/m^3 and a total alkali content raised to 1.25% Na_2O equivalent, by cement mass (total alkali content in the concrete mixture of 5.25 kg/m^3, Na_2O equivalent, is used in this test). It is also noted that in the case of critical structures such as those used for nuclear containment or large dams, a lower expansion limit may be required.

In the process of selecting preventive measures against ASR, the CSA Standard Practice A23.2-27A, proposed to classify the alkali-reactivity level of concrete aggregates, based on CSA A23.2-14A concrete prism expansions, as indicated below:

- One-year concrete prism expansion < 0.04%: non reactive
- 0.04 < one-year concrete prism expansion < 0.12%: moderately reactive
- One-year concrete prism expansion > 0.12%: highly reactive

Selecting and Evaluating Preventive Measures Against ASR

The CSA Standard Practice A23.2-28A [8] recognizes that the best test procedure to be used for evaluating the effectiveness of SCMs in preventing excessive expansion due to ASR is the CSA Test Method A23.2-14A. When conducting this test, it is recommended that:

- The water-to-binder ratio of the concrete mixture is adjusted to achieve a slump of 50 to 80 mm; the use of superplasticizer is permitted for concrete incorporating silica fume;
- additional alkali be added, in the form of NaOH, to bring the cement alkali content to 1.25% Na_2O equivalent for acceleration purposes;
- a testing period of two years is used, with an expansion limit of 0.04%.

Concrete Prism Expansion Data - Moderately-Reactive Aggregate Su

Control Concretes Made with the Low and High-Alkali Cements

Increasing expansions were obtained with increasing alkali content in the concrete mixture for the control test prisms incorporating the aggregate Su (Table 3-1). The test prisms cast from the control mixture made with the low-alkali cement C1 (Su L - M10) showed only limited expansion (i.e. < 0.020%) after six years of conditioning at 38°C and R.H. > 95% (Table 3-1). The test prisms cast from the control mixture made with the high-alkali cement C3, without and with added alkalies (Su - M11 and Su+ - M18), expanded by 0.035 and 0.075%, respectively, at one year, and 0.100 and 157% at two years (Table 3-1).

Concrete Mixtures Incorporating Fly Ash

None of the test prisms cast from fly ash concrete mixtures incorporating the Su aggregate showed significant trends of increasing expansion during the first 104 weeks of testing at 38°C and R.H. > 95% (Table 3-1). In fact, the maximum expansion value reached after 312 weeks of testing was 0.025%, obtained from test prisms cast from concrete mixture Su FA 20+ (M36) (Table 3-1). For a given fly ash content, similar expansions were obtained from test prisms cast from concrete mixtures without and with added alkalies.

Concrete Mixtures Incorporating Slag

None of the test prisms cast from the 50% and 65% slag concrete mixtures, both with and without added alkalies, showed significant expansion during the first 104 weeks of testing at 38°C and R.H. > 95% (Table 3-1). Test prisms cast from the concrete mixture incorporating 35% slag and added alkalies, i.e. Su Sg 35+ (M33), showed a slow, but steadily increasing expansion trend during the first 104 weeks of testing; however, the 0.04% expansion level was reached only after about 180 weeks of testing in the above condition (Table 3-1), which is much longer than the two-year testing period proposed by Standard Practice CSA A23.2-28A.

In the case of the concrete mixtures incorporating 50% slag, despite the addition of a large amount of alkalies in the mixture Su Sg 50++, the expansion remained well below the proposed 0.04% limit at two years. The 0.04% expansion level was reached after at 312 weeks of testing. It is to be The increase in alkalies in the mixture Su Sg 50++ was equivalent to the use of a cement with an alkali content of 1.6% Na_2Oeq.

Concrete Mixtures Incorporating Silica Fume

Decreasing expansions were obtained with increasing silica fume content in the silica fume concrete mixtures incorporating the aggregate Su (Table 3-1). For a given silica fume content, higher expansions were obtained from test prisms cast from concrete mixtures with added alkalies than from those without added alkalies.

None of the test prisms cast from the silica fume concrete mixtures incorporating the Su aggregate expanded more than 0.04% during the first 104 weeks of testing at 38°C and R.H. > 95%. Test prisms cast from concrete mixtures Su SF 7.5+ (M14) and Su SF 10+ (M15) reached the 0.04% expansion level after 156 and 208 weeks of testing, respectively (Table 3-1), which is longer than the two-year testing period proposed by Standard Practice CSA A23.2-28A.

Concrete Prism Expansion Data - Moderately-Reactive Aggregate Al

Control Concretes Made with the Low and High-Alkali Cements

Once again, increasing expansion for the control test prisms was obtained with increasing alkali content in the concrete mixtures incorporating the aggregate Al (Table 3-2). Test prisms cast from the control mixture made with the low-alkali cement C1 (Al L - M84) showed only limited expansion, i.e. about 0.03%, after 234 weeks of conditioning at 38°C and R.H. > 95%. Test prisms cast from the control mixtures made with the high-alkali cement C3, without and with added alkalies (Al - M78 and Al+ - M79), expanded by 0.028 and 0.090%, respectively, at one year; no significant additional expansion was observed afterwards.

Concrete Mixtures Incorporating Fly Ash

None of the test prisms cast from fly ash concrete mixtures incorporating the Al aggregate showed significant trends of increasing expansion during the first 104 weeks of testing at 38°C and R.H. > 95% (Table 3-2). The maximum expansion values reached after 104 weeks were 0.016% and 0.019%, obtained from test prisms cast from concrete mixtures Al FA 20+ (M95) and Al FA 30+++ (M98), respectively (Table 3-2).

In the case of the concrete mixtures incorporating 30% fly ash, even the addition of a large amount of alkalies in the mixture Al FA 30+++ was not sufficient to generate an expansion higher than the proposed 0.04% limit at two years; however, the 0.04% expansion level was reached after about 210 weeks. The increase in alkalies in the mixture Al FA 30+++ was equivalent to the use of a cement with an alkali content of about 1.8% Na_2Oeq, which is substantially high.

Concrete Mixtures Incorporating Silica Fume

For a given silica fume content, higher expansions were obtained from test prisms cast from concrete mixtures with added alkalies than from those without added alkalies (e.g. expansion Al SF 7.5 < expansion Al SF 7.5+); however, none of the test prisms cast from the silica fume concrete mixtures incorporating the Al aggregate expanded more than 0.04% during the first 104 weeks of testing. Test prisms cast from concrete mixtures Al SF 7.5+ (M81) and Al SF 10+ (M83) reached the 0.04% expansion limit after about 200 weeks of testing, which is much longer than the two-year testing period proposed by Standard Practice CSA A23.2-28A.

Table 3-1
Expansion Data for Concrete Prisms Incorporating Moderately-Reactive Aggregate Su, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)													
		1	4	8	18	26	52	78	104	130	156	182	234	286	312
Su L	M10	0.003	0.004	0.005	0.008	0.008	0.013	0.013	0.014	0.016	0.015	...	...	0.018	0.020
Su	M11	0.001	0.000	0.003	0.009	0.011	0.035	0.068	0.100	0.110	0.112	...	...	0.110	0.121
Su+	M18	0.000	-0.004	-0.006	0.008	0.019	0.075	0.122	0.157	0.184	0.191	0.185	...	0.172	0.181
Su FA 20	M35	0.006	0.003	0.001	0.000	0.001	0.001	0.002	0.003	0.006	...	0.007	0.002	0.014	0.017
Su FA 20+	M36	0.000	0.000	-0.004	-0.003	-0.001	0.001	0.005	0.008	0.006	...	0.011	0.008	0.024	0.025
Su FA 30	M39	-0.003	-0.004	-0.003	-0.004	-0.006	-0.004	-0.005	-0.007	-0.004	...	-0.006	-0.011	0.004	0.005
Su FA 30+	M40	-0.005	-0.011	-0.009	-0.009	-0.011	-0.008	-0.008	-0.007	-0.004	...	-0.004	0.000	0.007	0.009
Su FA 30++	M43	-0.002	-0.006	-0.007	-0.007	-0.008	-0.009	-0.006	-0.003	-0.003	...	-0.005	0.000	0.009	0.011
Su FA 56	M47	0.007	0.006	0.005	0.005	0.003	0.004	0.002	0.002	...	...	-0.003	-0.003	0.008	0.011
Su FA 56+	M48	0.009	0.008	0.006	0.007	0.007	0.008	0.006	0.008	...	...	0.004	0.005	0.016	0.018
Su Sg 35	M29	0.009	0.014	0.006	0.007	0.009	0.014	0.017	0.017	0.018	0.018	0.020	0.018	0.036	0.035
Su Sg 35+	M33	-0.005	0.004	0.006	0.009	0.013	0.021	0.028	0.034	0.036	...	0.043	0.040	0.057	0.060
Su Sg 50	M27	-0.002	0.002	0.003	0.004	0.006	0.006	0.007	0.006	0.007	0.007	0.008	0.004	0.018	0.020
Su Sg 50+	M28	-0.002	0.002	0.000	0.004	0.004	0.006	0.008	0.009	0.012	0.012	0.014	0.013	0.025	0.028
Su Sg 50++	M50	0.004	0.000	0.003	0.005	0.005	0.013	0.016	0.021	0.019	...	...	0.029	0.036	0.040
Su Sg 65	M31	0.000	0.001	-0.001	0.002	0.002	0.003	0.002	0.004	0.001	...	0.003	-0.002	0.012	0.013
Su Sg 65+	M32	0.003	0.002	0.003	0.005	0.005	0.005	0.006	0.007	0.006	...	0.008	0.003	0.019	0.021
Su SF 7.5	M12	-0.001	0.000	0.000	0.007	0.009	0.012	0.017	0.021	0.024	0.026	...	0.026	...	0.034
Su SF 7.5+	M14	-0.003	0.000	0.002	0.005	0.006	0.014	0.023	0.030	0.037	0.040	...	0.040	...	0.050
Su SF 10	M13	-0.003	-0.003	-0.002	0.004	0.009	0.009	0.011	0.013	0.016	0.018	...	0.018	...	0.028
Su SF 10+	M15	-0.008	0.000	0.000	0.004	0.007	0.013	0.019	0.023	0.032	0.037	...	0.044	...	0.050
Su SF 12.5	M16	-0.015	-0.009	-0.014	-0.009	-0.003	-0.001	0.002	0.000	0.001	0.003	...	0.001	...	0.009
Su SF 12.5+	M17	-0.014	-0.007	-0.011	-0.006	0.003	0.003	0.009	0.009	0.010	0.014	...	0.019	...	0.027

Table 3-2
Expansion Data for Concrete Prisms Incorporating Moderately-Reactive Aggregate Al, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)												
		1	4	8	18	26	52	78	104	130	156	182	208	234
Al L	M84	0.003	0.006	…	0.012	0.015	0.036	…	0.021	0.020	…	0.024	0.029	0.032
Al	M78	0.003	0.005	0.010	0.015	0.022	0.028	…	0.032	0.033	…	0.030	0.039	0.041
Al+	M79	0.001	0.008	0.014	0.038	0.057	0.090	…	0.092	0.097	…	0.094	0.101	0.103
Al FA 20	M94	-0.001	-0.005	-0.003	-0.002	0.000	0.007	0.008	0.007	…	0.019	0.024	0.025	0.025
Al FA 20+	M95	0.000	-0.005	0.000	0.001	0.005	0.011	0.014	0.016	…	0.027	0.032	0.033	0.034
Al FA 30	M96	-0.004	-0.009	-0.007	-0.007	-0.002	0.001	0.003	0.004	…	0.013	0.019	0.021	0.025
Al FA 30+	M97	0.001	0.000	-0.003	-0.002	0.003	0.007	0.011	0.011	…	0.023	0.029	0.032	0.033
Al FA 30+++	M98	-0.002	-0.004	-0.005	-0.003	0.001	0.010	0.016	0.019	…	0.030	0.035	0.038	0.040
Al SF 7.5	M80	…	-0.001	0.002	0.002	0.008	0.006	…	0.006	0.016	…	0.016	0.023	0.025
Al SF 7.5+	M81	…	0.003	0.004	0.006	0.011	0.018	…	0.028	0.031	…	0.032	0.039	0.041
Al SF 10	M82	…	-0.003	0.000	0.003	0.004	0.009	…	0.014	0.016	…	0.022	0.025	0.028
Al SF 10+	M83	…	-0.004	0.000	0.005	0.007	0.011	...	0.028	0.029	...	0.039	0.044	0.047

Table 3-3
Expansion Data for Concrete Prisms Incorporating Moderately-Reactive Aggregate Wy, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)								
		1	4	8	18	26	52	78	104	130
Wy+	M168	-0.007	-0.006	0.004	0.042	0.065	0.090	0.099	0.093	0.090
Wy FA 20+	M169	0.002	-0.001	0.001	0.004	0.013	0.020	0.027	0.030	0.037
Wy FA 30+	M170	-0.008	-0.017	-0.014	-0.008	0.000	0.005	0.010	0.013	0.020

Concrete Prism Expansion Data - Moderately-reactive Aggregate Wy

Control Concrete Made with the High-Alkali Cement

Test prisms cast from the control mixture made with the high-alkali cement C4 and added alkalies (Wy+ - M168) expanded by 0.090% at one year; no significant additional expansion was observed afterwards (Table 3-3).

Concrete Mixtures Incorporating Fly Ash

Test prisms cast from the concrete mixture incorporating 20% fly ash and added alkalies (Wy FA 20+ - M169) showed a slow expansion that reached 0.030 and 0.037% after 104 and 130 weeks of testing, respectively (Table 3-3). In the case of the 30% fly ash mixture, i.e. Wy FA 30+ (M170), a limited expansion of 0.013% was reached after 104 weeks (Table 3-3); this is well below the 0.04% expansion limit proposed by Standard Practice CSA A23.2-28A.

Concrete Prism Expansion Data - Highly-Reactive Aggregate Po

Control Concretes Made with the Low and High-Alkali Cements

Test prisms cast from the control mixture made with the low-alkali cement C1 (Po L - M70) showed a slow, but steadily increasing expansion trend, which levelled off at about 0.030% after 52 weeks of conditioning at 38°C and R.H. > 95% (Table 3-4). Concrete prisms cast from the control mixtures incorporating the high-alkali cement C3, without and with added alkalies (i.e. Po - M62 and Po+ - M63), reached expansions of 0.142 and 0.130%, respectively, after 52 weeks of testing (Table 3-4).

Concrete Mixtures Incorporating Fly Ash

Test prisms cast from the 30% fly ash concrete mixture, i.e. Po FA 30+ (M71), did not show any significant expansion during the first 104 weeks of testing (Table 3-4). The maximum expansion value reached after 312 weeks was about 0.040%.

Concrete Mixtures Incorporating Silica Fume

Test prisms cast from concrete mixtures incorporating 7.5% and 10% silica fume showed a slow but steadily increasing expansion trend that really started after about 6 months of testing at 38°C and R.H. > 95% (Table 3-4). The 0.04% expansion level was reached for test prisms made from the above mixtures with added alkalies between 65 to 78 weeks of testing (Table 3-4).

Table 3-4
Expansion Data for Concrete Prisms Incorporating Highly-Reactive Aggregate Po, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)													
		1	4	8	18	26	52	78	104	130	169	221	234	286	312
Po L	M70	0.005	0.012	0.013	0.017	0.023	0.030	0.030	0.031	0.030	0.030	0.030	0.032	0.037	0.039
Po	M62	0.000	0.003	0.007	0.030	...	0.142	0.198	0.226	0.231	0.236	0.234	0.239	0.248	0.249
Po+	M63	0.000	0.001	0.005	0.034	...	0.130	0.168	0.226	…	0.266	0.268	0.277	0.289	0.290
Po FA 30+	M71	0.005	0.004	0.003	0.002	0.003	0.008	0.010	0.015	0.018	0.022	0.020	0.028	0.037	0.038
Po SF 7.5	M67	0.000	0.000	0.002	0.004	0.008	0.019	0.029	0.041	0.053	0.060	0.070	0.072	0.082	0.084
Po SF 7.5+	M68	0.000	0.005	0.007	0.011	0.017	0.033	0.051	0.073	0.094	0.108	0.127	0.129	0.140	0.141
Po SF 10+	M69	0.000	0.002	0.005	0.009	0.016	0.028	0.039	0.054	0.070	0.084	0.097	0.105	0.122	0.129

Concrete Prism Expansion Data - Highly-Reactive Aggregate Sp

Control Concretes Made with the Low and High-Alkali Cements

Test prisms cast from the control mixture made with the low-alkali cement C1 (Sp L - M26) showed a slow, but steadily increasing expansion, that reached 0.029 and 0.057% after 104 and 312 weeks of conditioning at 38°C and R.H. > 95%, respectively (Table 3-5). Test prisms cast from the control mixture made with the high-alkali cement C3, without and with added alkalies (Sp – M34 and Sp+ - M25), expanded by 0.137% and 0.184%, respectively, at one year, and by 0.171% and 0.207% at two years (Table 3-5). The test prisms did not expand significantly more afterwards.

Concrete Mixtures Incorporating Fly Ash

None of the test prisms cast from fly ash concrete mixtures incorporating the Spratt aggregate expanded in excess of 0.04% after 104 weeks of testing at 38°C and R.H. > 95%. The expansion values after 312 weeks of testing ranged from 0.012 to 0.035%. Limited expansion was obtained with the test prisms cast from concrete mixture Sp FA 30++ (M44), despite the high alkali content in that mixture at 4.12 kg/m^3; this was equivalent to using a cement with an alkali content of about 1.4% Na_2Oeq.

Concrete Mixtures Incorporating Slag

Test prisms cast from the concrete mixture incorporating 35% slag (i.e. Sp Sg 35% - M30) showed a slow, but steadily increasing expansion, that reached 0.027% and 0.050% after 104 and 312 weeks of testing, respectively (Table 3-5). The above mixture was made without added alkalies.Hence, for test prisms cast from a concrete mixture incorporating 35% slag and added alkalies, the two-year expansion would most likely have exceeded the 0.04% limit.

The expansion of test prisms was found to increase with increasing alkali content in the 50% slag mixtures, i.e. expansion of Sp Sg 50 (M37) < expansion of Sp Sg 50+ (M38) < expansion of Sp Sg 50++ (M45); however, the maximum expansion reached after 104 weeks of testing was still relatively limited for these prisms, i.e. < 0.025%. The increased alkali content in the mixture Sp Sg 50 ++ was equivalent to the use of a cement with an alkali content of about 1.6% Na_2Oeq. Test prisms cast from the 65% slag concrete mixture (mixture without added alkali) showed limited expansion during the first 104 weeks of testing at 38°C and R.H. > 95% (Table 3-5).

Concrete Mixtures Incorporating Silica Fume

Test prisms cast from concrete mixtures incorporating 7.5% silica fume, i.e. Sp SF 7.5 (M64), showed a slow but steadily increasing expansion trend during the first 104 weeks of testing at 38°C, R.H. > 95%. The 104-week expansion value of 0.027% (0.054% at 312 weeks) for prisms tested at 38°C and R.H. > 95% is still relatively limited; however, this mixture was made without the addition of NaOH to the mixing water. Therefore, expansions in excess of the 0.04% limit at two years would most likely be possible for test prisms cast from a concrete mixture incorporating 7.5% silica fume and added alkalies. This conclusion is supported by the expansion data obtained from the test prisms incorporating 10% silica fume, made with and without added alkalies. At the end of the 104-week testing period, test prisms cast from mixture Sp SF 10+ (M66) showed an average expansion of 0.038%, whereas that of test prisms from mixture Sp SF 10 was only 0.021%. That is, the expansion almost doubled with added alkalies (Table 3-5). Test prisms cast from 12.5% silica fume concrete mixture (Sp SF 12.5 – M58) did not show any significant expansion during the first 104 weeks of testing; however, this mixture was made without the addition of NaOH to the mixing water.

Concrete Prism Expansion Data - Highly-Reactive Aggregate Con

Control Concretes Made with the Low and High- Alkali Cements

Increase in concrete prism expansion was observed with increasing total alkali content of the concrete mixtures, i.e. expansion of Con L (M87) < expansion of Con (M85) < expansion of Con+ (M86). Test prisms cast from the control mixture made with the low-alkali cement C1 (ConL - M87) showed limited expansion (< 0.025%) even after 234 weeks of conditioning at 38°C and R.H. > 95% (Table 3-6). Test prisms cast from the control mixture made with the high-alkali cement C3, without and with added alkalies (Con and Con+), expanded by 0.092 and 0.196%, respectively, at one year. The above sets of test prisms reached 0.125 and 0.221% expansion at two years, respectively, and did not expand significantly afterwards (Table 3-6).

Concrete Mixtures Incorporating Fly Ash

Test prisms cast from the concrete mixture incorporating 20% fly ash and added alkalies (Con FA 20+ - M89) showed increasing expansion which reached just about 0.040% after 104 weeks of testing at 38°C and R.H. > 95% (Table 3-6). A similar trend was observed for the set of test prisms cast from concrete mixture Con FA 30+++ (M99) (Table 3-6); the expansions reached 0.035% at 104 weeks. The increased alkalies in the mixture Con FA 30+++ was equivalent to the use of a cement with an alkali content of about 1.8% Na_2Oeq. Test prisms cast from the 56% fly ash concrete mixture (mixture without added alkali) showed limited expansion during the first 104 weeks of testing at 38°C and R.H. > 95% (Table 3-6).

Concrete Mixtures Incorporating Silica Fume

Test prisms cast from the silica fume mixture Con SF 7.5 (M76) showed a slow, but steadily increasing expansion, which reached 0.042 and 0.067% after 104 and 234 weeks of testing, respectively (Table 3-6). Test prisms cast from mixture Con SF 10 (M77) showed a similar trend, reaching expansions of 0.031 and 0.056% after the same periods of testing (Table 3-6). The above mixtures were made without added alkalies, and the results suggest the limited effect of 7.5 and 10% silica fume to control ASR expansion with the highly-reactive Con aggregate.

Table 3-5
Expansion Data for Concrete Prisms Incorporating Highly-Reactive Aggregate Sp, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)												
		1	4	8	18	26	52	78	104	130	182	234	286	312
Sp L	M26	0.005	0.012	0.011	0.016	0.020	0.024	0.027	0.029	0.033	...	0.038	0.054	0.057
Sp	M34	0.003	0.008	0.021	0.074	0.097	0.137	0.162	0.171	0.175	...	0.172	0.184	0.184
Sp+	M25	-0.005	0.004	0.014	0.069	0.124	0.184	0.202	0.207	0.208	0.210	0.211	0.223	0.225
Sp FA 20	M57	0.008	0.012	0.010	0.010	0.011	0.015	0.017	0.019	0.018	...	0.026	0.035	0.035
Sp FA 30	M41	0.001	-0.004	-0.004	-0.006	-0.008	-0.005	-0.004	-0.001	-0.001	0.000	0.003	0.011	0.012
Sp FA 30+	M42	0.002	-0.001	-0.002	-0.004	-0.003	0.000	0.003	0.007	0.007	0.008	0.013	0.021	0.024
Sp FA 30++	M44	0.001	-0.004	-0.006	-0.007	-0.007	-0.004	0.000	0.004	0.003	0.004	0.004	0.019	0.020
Sp Sg 35	M30	0.000	...	0.002	0.005	0.007	0.018	0.023	0.027	0.028	0.032	0.032	0.048	0.050
Sp Sg 50	M37	-0.003	-0.005	-0.006	-0.002	-0.004	0.001	0.005	0.008	0.009	0.012	0.010	0.026	0.028
Sp Sg 50+	M38	-0.002	-0.001	-0.003	0.000	0.000	0.006	0.012	0.014	0.017	0.020	0.020	0.034	0.037
Sp Sg 50++	M45	0.000	-0.001	-0.002	0.002	0.006	0.012	0.018	0.025	...	0.029	0.032	0.048	0.051
Sp Sg 65	M46	0.001	0.001	0.001	0.003	0.008	0.008	0.011	0.015	...	0.015	0.017	0.030	0.033
Sp SF 7.5	M64	0.002	0.003	0.005	0.008	0.010	0.016	0.022	0.027	...	...	0.042	0.052	0.054
Sp SF 10	M65	-0.002	0.002	0.004	0.009	0.009	0.012	0.017	0.021	...	...	0.034	0.043	0.046
Sp SF 10+	M66	-0.002	0.000	0.003	0.006	0.009	0.019	0.028	0.038	0.043	...	0.066	0.073	0.076
Sp SF 12.5	M58	0.000	0.000	0.003	0.005	0.007	0.010	0.013	0.017	0.016	...	0.027	0.036	0.039

Table 3-6
Expansion Data for Concrete Prisms Incorporating Highly-Reactive Aggregate Con, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)												
		1	4	8	18	26	52	78	104	130	156	182	208	234
Con L	M87	0.001	0.004	0.007	0.003	0.010	0.008	0.009	0.006	0.004	0.016	0.024	0.022	0.023
Con	M85	0.004	0.010	0.005	0.022	0.055	0.092	0.121	0.125	0.124	0.142	0.149	0.151	0.150
Con +	M86	-0.004	0.000	0.010	0.069	0.137	0.196	0.210	0.221	0.224	0.244	0.251	0.255	0.254
Con FA 20	M88	-0.001	0.000	-0.003	0.006	0.004	0.015	0.022	0.026	…	0.043	0.052	0.056	0.057
Con FA 20+	M89	0.003	-0.003	-0.002	0.009	0.011	0.025	0.034	0.040	…	0.062	0.071	0.089	0.080
Con FA 30	M90	-0.001	-0.005	-0.006	-0.004	-0.002	0.006	0.011	0.012	…	0.026	0.033	0.036	0.037
Con FA 30+	M91	0.000	-0.005	-0.004	-0.001	0.003	0.012	0.017	0.020	…	0.037	0.045	0.052	0.051
Con FA 30+++	M99	...	-0.001	0.003	0.010	0.012	0.022	0.030	0.035	0.039	0.055	0.059	0.066	0.065
Con FA 56	M92	0.003	-0.005	-0.002	-0.001	-0.002	-0.001	0.001	-0.001	…	0.005	0.012	0.010	0.010
Con FA 56+	M93	0.003	-0.002	0.002	0.002	0.003	0.005	0.005	0.005	…	0.011	0.016	0.017	0.018
Con SF 7.5	M76	0.004	0.007	0.006	0.010	0.009	0.019	0.034	0.042	…	0.046	0.048	0.063	0.067
Con SF 10	M77	-0.001	0.000	0.003	0.006	0.008	0.013	0.025	0.031	…	0.036	0.036	0.044	0.056

Concrete Prism Expansion Data - Highly-Reactive Aggregate Sl

Control Concretes Made with the Low and High- Alkali Cements

Increasing concrete prism expansions were observed with increasing total alkali content of the concrete mixtures, i.e. expansion of Sl L (M1) < expansion of Sl (M2) < expansion of Sl+ (M3) (Table 3-7) Test prisms cast from the control mixture made with the low-alkali cement C1 (Sl L - M1) showed only limited expansion, i.e. < 0.030%, after six years of testing at 38°C and R.H. > 95% (Table 3-7). Test prisms cast from the control mixture made with the high-alkali cement C3, without and with added alkalies (Sl and Sl+), expanded by 0.174 and 0.221%, respectively, at one year (Table 3-7). The above sets of test prisms reached 0.236 and 0.270% expansion at two years, respectively, and did not expand significantly afterwards (Table 3-6).

Concrete Mixtures Incorporating Fly Ash

Test prisms cast from concrete mixtures incorporating 20% fly ash showed a slow, but steadily increasing expansion during the first 104 weeks of testing at 38°C and R.H. > 95% (Table 3-7). A two-year expansion of 0.050% was obtained for test prisms Sl FA 20+ (M20) (Table 3-7). A similar trend of increasing expansion was also observed for the 30% fly ash mixtures (with and without added alkalies); however, test prisms cast from the fly ash mixture Sl FA 30+ (M22) expanded by only 0.021% after 104 weeks of testing (Table 3-7). None of the test prisms cast from 56% fly ash concrete mixtures, with and without added alkalies, showed significant expansion after 312 weeks of testing at 38°C and R.H. > 95% (Table 3-7).

Concrete Mixtures Incorporating Silica Fume

Expansions at specific ages for test prisms made with the Sl aggregate were found to decrease with increasing silica fume content in the concrete mixture. Again, for a given silica fume content, higher expansions were obtained from test prisms cast from silica fume concrete mixtures with added alkalies than from those without added alkalies.

Test prisms cast from concrete mixtures Sl SF 7.5+ (M6) and Sl SF 10+ (M7) reached the 0.04% expansion limit after about 70 and 104 weeks of testing, respectively (Table 3-7); after six years, the test prisms cast from the above mixtures expanded by 0.109 and 0.064%, respectively (Table 3-7). The test prisms incorporating 12.5% silica fume and added alkalies, i.e. Sl SF 12.5+, expanded by only 0.016% at 104 weeks.

Table 3-7
Expansion Data for Concrete Prisms Incorporating Highly-Reactive Aggregate SI, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)													
		1	4	8	18	26	52	78	104	130	156	195	234	260	312
SI L	M1	0.000	0.003	0.006	0.011	0.015	0.018	0.017	0.018	0.018	0.017	0.010	0.020	0.023	0.027
SI	M2	-0.006	-0.001	-0.002	0.013	0.038	0.174	0.226	0.236	0.239	0.243	0.234	0.242	0.249	0.252
SI+	M3	-0.004	0.003	0.009	0.092	0.143	0.221	0.257	0.270	0.270	0.273	0.263	0.271	0.280	0.279
SI FA 20	M19	0.008	0.006	0.005	0.007	0.011	0.014	0.019	0.022	0.023	0.028	0.031	0.031	0.040	0.047
SI FA 20+	M20	0.007	0.003	0.004	0.007	0.011	0.027	0.041	0.050	0.053	0.061	0.065	0.068	0.075	0.084
SI FA 30	M21	0.005	0.004	0.007	0.006	0.009	0.009	0.013	0.015	0.015	0.021	0.022	0.022	0.031	0.036
SI FA 30+	M22	0.000	-0.001	0.005	0.003	0.005	0.011	0.017	0.021	0.023	0.028	0.031	0.031	0.041	0.048
SI FA 56	M23	0.002	0.000	0.000	-0.002	0.000	0.002	0.002	0.002	0.001	0.000	0.002	0.003	0.007	0.012
SI FA 56+	M24	0.006	0.004	0.008	0.004	0.006	0.007	0.007	0.006	0.007	0.004	0.005	0.004	0.012	0.016
SI SF 7.5	M4	-0.011	-0.008	0.000	0.000	0.008	0.007	0.010	0.019	0.020	0.022	0.013	0.024	0.026	0.034
SI SF 7.5+	M6	-0.015	-0.007	0.002	-0.001	0.009	0.020	0.053	0.079	0.089	0.093	0.090	0.100	0.099	0.109
SI SF 10	M5	-0.010	-0.003	-0.001	0.004	0.014	0.010	0.012	0.019	0.017	0.018	0.010	0.023	0.022	0.034
SI SF 10+	M7	-0.020	-0.011	-0.001	-0.003	0.008	0.013	0.025	0.039	0.043	0.049	0.041	0.054	0.057	0.064
SI SF 12.5	M8	-0.010	-0.005	-0.004	0.001	0.004	0.009	0.010	0.013	0.013	0.016	0.004	...	0.017	0.026
SI SF 12.5+	M9	-0.014	-0.009	-0.006	-0.002	0.002	0.008	0.010	0.016	0.021	0.024	0.016	...	0.032	0.042

Concrete Prism Expansion Data - Highly-Reactive Aggregate NM

Control Concretes Made with the High-Alkali Cement

Test prisms cast from the control mixture made with the high-alkali cement C4 (NM - M111), but without added alkalies, showed an expansion of 0.212% after one year of testing at 38°C and R.H. > 95% (Table 3-8). The test prisms did not expand significantly afterwards.

Concrete Mixtures Incorporating Fly Ash

Test prisms cast from concrete mixtures incorporating 20% fly ash, i.e. NM FA 20+ (M160), showed a steadily increasing expansion during the first 104 weeks of testing at 38°C and R.H. > 95%; the prisms reached a two-year expansion of 0.085% (Table 3-8). A similar trend of increasing expansion was also observed for the 30% fly ash concrete mixture, i.e. NM FA 30+ (M161); the prisms reached a two-year expansion of 0.050% (Table 3-8).

Table 3-8
Expansion Data for Concrete Prisms Incorporating Highly-Reactive Aggregate NM, and Stored at 38°C & R.H. > 95%

Concrete Mixture Designation		Expansion (%) Against Time (Weeks)								
		1	4	8	18	26	52	78	104	130
NM	M111	0.008	0.075	0.130	0.177	0.199	0.212	…	0.231	0.237
NM FA 20+	M160	0.003	0.000	0.006	0.020	0.029	0.054	0.072	0.085	0.096
NM FA 30+	M161	0.006	0.001	0.002	0.007	0.015	0.031	0.037	0.050	0.056

Results of AAR Expansion Testing in the Field – Length Changes in Concrete Beams and Slabs

Moderately-Reactive Aggregate Su

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slabs incorporating the Aggregate Su and made with low- and high-alkali cements are given in Table 3-9.

The control beams and slab incorporating the low-alkali cement C1 and the aggregate Su, i.e. Su L (M10), have not shown any significant expansion after about 360 weeks of outdoor exposure. The control beams and slab incorporating the aggregate Su and the high-alkali cement, i.e. Su (M11), have reached average expansions of 0.032 and 0.034%, respectively, after 360 weeks of

outdoor exposure (Table 3-9). The average expansions reached by the control beams and slab with added alkalies, i.e. Su+ (M18), were 0.042 and 0.061%, respectively, after 352 weeks of outdoor exposure (Table 3-9).

Concrete Mixtures Incorporating Fly Ash

None of the concrete beams and slabs incorporating fly ash and the Aggregate Su has expanded significantly after 6 years of testing outdoors (Table 3-9). The average expansions obtained ranged from –0.015 to 0.011%.

Concrete Mixtures Incorporating Slag

None of the concrete beams and slabs incorporating slag and the Aggregate Su has shown significant expansion after 6 years of testing outdoors (Table 3-9). The average expansions obtained ranged from 0.002 to 0.021%. The highest expansion of 0.021% was obtained for the slab specimen Su Sg 35+.

Concrete Mixtures Incorporating Silica Fume

None of the concrete beams and slabs incorporating silica fume and the Aggregate Su has expanded significantly after 7 years of testing outdoors (Table 3-9). The average expansions obtained ranged from 0.004 to 0.014%.

Table 3-9
Expansion Data for Concrete Beams and Slabs Made with Aggregate Su, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)												
			31	*39*	*48*	*88*	*98*	*105*	*137*	*153*	*194*	*247*	*299*	*312*	*360*
Su L	***M10***	**Slab Average**	0.008	0.008	0.007	0.005	0.008	0.006	0.016	-0.006	0.000	-0.001	0.000	-0.005	-0.003
		Average Beams A & B	0.001	0.001	-0.004	0.000	0.002	-0.004	-0.006	0.003	0.003	0.002	0.011	0.008	0.009
			31	*39*	*48*	*88*	*98*	*105*	*137*	*153*	*194*	*247*	*299*	*312*	*360*
Su	***M11***	**Slab Average**	-0.004	-0.004	-0.007	-0.005	-0.002	-0.007	0.008	-0.003	0.000	0.009	0.025	0.030	0.034
		Average Beams A & B	0.002	0.002	-0.004	-0.001	0.001	-0.004	-0.006	0.005	0.006	0.015	0.026	0.029	0.032
			29	*38*	*86*	*95*	*104*	*132*	*148*	*190*	*242*	*294*	*304*	*352*	
Su+	***M18***	**Slab Average**	0.002	0.001	0.004	0.006	0.000	0.000	0.009	0.014	0.026	0.044	0.051	0.061	
		Average Beams A & B	0.000	-0.006	-0.001	0.001	-0.006	-0.005	0.004	0.007	0.019	0.035	0.039	0.042	
			31	*39*	*48*	*87*	*98*	*105*	*136*	*148*	*194*	*245*	*298*	*304*	*352*
Su SF 7.5	***M12***	**Slab Average**	-0.010	-0.009	-0.012	-0.008	-0.007	-0.012	0.007	-0.006	0.000	0.005	0.009	0.007	0.007
		Average Beams A & B	0.003	0.002	-0.003	0.001	0.002	-0.003	-0.005	0.005	0.005	0.008	0.015	0.014	0.012
			30	*38*	*46*	*86*	*94*	*104*	*134*	*148*	*193*	*245*	*297*	*310*	*358*
Su SF 7.5+	***M14***	**Slab Average**	-0.007	-0.008	-0.010	-0.003	-0.001	-0.008	0.010	-0.003	-0.001	0.005	0.009	0.010	0.011
		Average Beams A & B	-0.003	-0.002	-0.008	-0.003	-0.001	-0.006	-0.005	0.003	0.002	0.008	0.015	0.015	0.014
			31	*39*	*48*	*87*	*98*	*105*	*136*	*148*	*194*	*245*	*298*	*304*	*352*
Su SF 10	***M13***	**Slab Average**	0.007	0.006	0.000	0.007	0.009	0.004	0.010	-0.001	0.002	0.006	0.010	0.004	0.007
		Average Beams A & B	-0.001	0.000	-0.001	0.003	0.004	-0.001	-0.003	0.007	0.006	0.009	0.017	0.016	0.014
			30	*38*	*46*	*86*	*94*	*104*	*134*	*148*	*193*	*245*	*297*	*310*	*358*
Su SF 10+	***M15***	**Slab Average**	-0.006	-0.007	-0.017	-0.009	-0.006	-0.018	-0.002	-0.019	-0.008	-0.004	0.004	0.004	0.004
		Average Beams A & B	-0.001	0.001	-0.007	-0.001	0.001	-0.006	-0.004	0.005	0.004	0.007	0.016	0.015	0.013

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)												
			30	*38*	*46*	*86*	*94*	*104*	*134*	*148*	*193*	*245*	*297*	*310*	*358*
Su SF 12.5	***M16***	**Slab Average**	0.008	0.010	0.005	0.010	0.010	0.005	0.000	0.000	-0.001	0.003	0.008	0.007	0.005
		Average Beams A & B	0.000	0.002	-0.004	0.001	0.002	-0.004	-0.004	0.005	0.005	0.009	0.016	0.016	0.014
			30	*38*	*46*	*86*	*94*	*104*	*134*	*148*	*193*	*245*	*297*	*310*	*358*
Su SF 12.5+	***M17***	**Slab Average**	0.009	0.005	0.000	0.000	0.004	-0.001	-0.001	0.004	0.000	0.011	0.015	0.015	0.012
		Average Beams A & B	0.002	0.002	-0.006	0.000	0.002	-0.005	-0.004	0.004	0.004	0.012	0.016	0.014	0.012
			46	*58*	*65*	*97*	*110*	*121*	*154*	*220*	*258*	*271*	*319*		
Su FA 20	***M35***	**Slab Average**	-0.001	-0.001	0.002	0.000	-0.012	-0.016	-0.007	0.000	0.006	0.005	0.006		
		Average Beams A & B	-0.005	-0.002	-0.022	-0.010	-0.006		-0.006	0.000	0.003	0.002	0.001		
			46	*58*	*65*	*97*	*110*	*125*	*154*	*220*	*258*	*271*	*319*		
Su FA 20+	***M36***	**Slab Average**	0.002	0.001	-0.024	0.003	-0.006	-0.012	-0.004	0.003	0.011	0.009	0.011		
		Average Beams A & B	-0.004	-0.002	-0.021	-0.008	-0.007		-0.007	0.000	0.004	0.004	0.003		
			43	*56*	*92*	*104*	*120*	*150*	*216*	*254*	*267*	*315*			
Su FA 30	***M39***	**Slab Average**	-0.015	-0.002	-0.002	-0.013	-0.017	-0.013	-0.006	-0.003	-0.003	-0.005			
		Average Beams A & B	-0.007	-0.007	-0.007	-0.005		-0.005	0.001	0.004	0.002	0.000			
			43	*56*	*92*	*104*	*150*	*151*	*216*	*254*	*267*	*315*			
Su FA 30+	***M40***	**Slab Average**	-0.016	-0.009	-0.001	-0.014	-0.018	-0.013	-0.006	-0.001	-0.001	-0.002			
		Average Beams A & B	-0.008	-0.005	-0.010	-0.008		-0.008	0.000	0.003	0.001	-0.001			
			41	*57*	*91*	*103*	*215*	*253*	*301*	*267*	*315*				
Su FA 30++	***M43***	**Slab Average**	-0.006	-0.002	0.004	-0.007	0.009	0.009	0.010	-0.006	-0.006				
		Average Beams A & B	-0.001	-0.003	-0.005	-0.002	0.014	0.007	0.003	-0.002	-0.002				

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)										
			40	*54*	*90*	*103*	*120*	*147*	*213*	*215*	*264*	*312*	
Su FA 56	***M47***	**Slab Average**	-0.014	-0.009	-0.004	-0.020	-0.027	-0.019	-0.014	-0.010	-0.008	-0.015	
		Average Beams A & B	-0.002	-0.003	-0.004	-0.005		-0.005	0.000	0.001	0.001	-0.004	
			40	*54*	*90*	*103*	*119*	*147*	*213*	*251*	*264*	*312*	
Su FA 56+	***M48***	**Slab Average**	0.004	0.002	0.015	0.000	-0.006	0.003	0.007	0.010	0.013	0.010	
		Average Beams A & B	0.001	-0.002	-0.002	-0.002	0.000	-0.003	0.001	0.007	0.006	0.005	
			47	*39*	*66*	*98*	*111*	*122*	*155*	*221*	*259*	*272*	*320*
Su Sg 35	***M29***	**Slab Average**	0.001	0.006	-0.019	0.007	-0.003	-0.005	0.002	0.006	0.011	0.006	0.013
		Average Beams A & B	-0.005	0.000	-0.016	-0.009	-0.005		-0.002	0.003	0.007	0.006	0.006
			47	*57*	*65*	*96*	*109*	*124*	*154*	*221*	*259*	*272*	*320*
Su Sg 35+	***M33***	**Slab Average**	0.004	0.002	-0.018	0.009	0.000	-0.005	0.004	0.011	0.017	0.016	0.021
		Average Beams A & B	0.000	-0.001	-0.017	-0.009	0.000		0.000	0.005	0.011	0.010	0.010
			49	*60*	*67*	*98*	*110*	*125*	*156*	*223*	*259*	*273*	*321*
Su Sg 50	***M27***	**Slab Average**	0.010	0.007	-0.010	-0.013	-0.004	0.001	0.006	0.011	0.015	0.011	0.015
		Average Beams A & B	0.006	0.001	-0.009	0.003	0.008		0.009	0.012	0.016	0.014	0.014
			49	*60*	*67*	*98*	*110*	*125*	*156*	*223*	*259*	*273*	*321*
Su Sg 50+	***M28***	**Slab Average**	0.011	0.008	-0.008	0.015	0.005	0.003	0.008	0.013	0.017	0.014	0.018
		Average Beams A & B	0.001	0.003	-0.014	-0.005	0.002		0.003	0.005	0.014	0.012	0.013
			47	*39*	*66*	*98*	*111*	*122*	*155*	*221*	*259*	*272*	*320*
Su Sg 65	***M31***	**Slab Average**	0.004	0.002	-0.018	0.010	-0.003	-0.006	0.000	0.005	0.009	0.008	0.011
		Average Beams A & B	-0.002	-0.002	-0.020	-0.013	-0.006		-0.004	-0.001	0.006	0.003	0.003
			47	*39*	*66*	*98*	*111*	*122*	*155*	*227*	*259*	*272*	*320*
Su Sg 65+	***M32***	**Slab Average**	0.002	-0.001	-0.018	0.010	-0.004	-0.006	0.001	0.005	0.009	0.009	0.012
		Average Beams A & B	-0.006	-0.005	-0.020	-0.013	-0.008		-0.006	-0.003	0.004	0.003	0.002

Table 3-10
Expansion Data for Concrete Beams and Slabs Made with Aggregate AI, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)				
			30	*48*	*143*	*192*	*240*
AI L	***M84***	**Slab Average**	-0.006	0.014	0.022	0.019	0.021
		Average Beams A & B	0.004	0.010	0.009	0.015	0.017
			34	*48*	*143*	*195*	*243*
AI	***M78***	**Slab Average**	0.017	0.003	0.025	0.045	0.061
		Average Beams A & B	0.001	0.007	0.005	0.018	0.027
			34	*48*	*143*	*195*	*243*
AI+	***M79***	**Slab Average**	0.013	0.002	0.026	0.049	0.070
		Average Beams A & B	0.001	0.005	0.008	0.028	0.047
			30	*50*	*143*	*195*	*243*
AI SF 7.5	***M80***	**Slab Average**	0.016	0.017	0.013	0.010	0.010
		Average Beams A & B	-0.002	0.003	0.001	0.006	0.006
			30	*43*	*143*	*195*	*243*
AI SF 7.5+	***M81***	**Slab Average**		0.010	0.019	0.015	0.017
		Average Beams A & B	-0.002	0.007	0.006	0.007	0.009
			30	*50*	*143*	*199*	*247*
AI SF 10	***M82***	**Slab Average**	0.024	0.012	0.022	0.018	0.018
		Average Beams A & B	0.000	0.009	0.006	0.011	0.012
			30	*43*	*143*	*195*	*243*
AI SF 10+	***M83***	**Slab Average**	-0.003		-0.002	-0.007	-0.004
		Average Beams A & B	-0.001	0.006	0.001	0.007	0.009
			30	*143*	*199*	*247*	
AI FA 20	***M94***	**Slab Average**	-0.013	0.000	-0.003	0.000	
		Average Beams A & B	-0.011	-0.013	-0.008	-0.007	
			52	*103*	*153*	*201*	
AI FA 20+	***M95***	**Slab Average**	-0.005	0.005	0.005	0.008	
		Average Beams A & B	-0.009	-0.012	-0.007	-0.005	
			52	*102*	*153*	*201*	
AI FA 30	***M96***	**Slab Average**	-0.013	-0.004	-0.006	-0.004	
		Average Beams A & B	-0.002	0.001	0.001	0.002	
			52	*102*	*153*	*201*	
AI FA 30+	***M97***	**Slab Average**	-0.007	0.002	0.000	0.001	
		Average Beams A & B	-0.004	-0.001	-0.002	0.000	
			52	*102*	*153*	*201*	
AI FA 30++	***M98***	**Slab Average**	-0.013	-0.005	-0.007	-0.005	
		Average Beams A & B	-0.002	0.000	0.000	0.002	

Moderately-Reactive Aggregate Al

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slabs incorporating the Aggregate Al and made with low- and high-alkali cements are given in Table 3-10.

The control beams and slab incorporating the low-alkali cement C1 and the aggregate Al, i.e. Al L (M84), have not shown significant expansion after 240 weeks of testing outdoors. The control beams and slab incorporating the aggregate Al and the high-alkali cement, i.e. Al (M78), have reached average expansions of 0.027 and 0.061%, respectively, after 243 weeks of outdoor exposure; the average expansions reached by the control beams and slab Al+ (M79) made with added alkalies, were 0.047 and 0.070%, respectively, after 243 weeks of testing outdoors (Table 3-10).

Concrete Mixtures Incorporating Fly Ash

None of the concrete beams and slabs incorporating fly ash and the Aggregate Al has expanded significantly after 200 to 247 weeks of testing outdoors (Table 3-10). The average expansions obtained ranged from –0.007 to 0.008%, including the concrete Al FA 30+++ (M98) which had the total alkali content raised to 5.25 kg/m^3.

Concrete Mixtures Incorporating Silica Fume

None of the concrete beams and slabs incorporating silica fume and the Aggregate Al has expanded significantly after about 245 weeks of testing outdoors (Table 3-10). The average expansions obtained ranged from –0.004 to 0.018%.

Highly-Reactive Aggregate Po

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slabs incorporating the Aggregate Po and made with low- and high-alkali cements, are given in Table 3-11. The control beams and slab incorporating the low-alkali cement C1 and the aggregate Po, i.e. Po L (M70), have not shown any significant expansion after about 300 weeks of testing outdoors. The control beams and slab made with the high-alkali cement, i.e. Po (M62), have reached average expansions of 0.017 and 0.067%, respectively, after about 300 weeks of outdoor exposure; the expansions reached by the control beams and slab Po+ (M63) made with added alkalies, were 0.018 and 0.057%, respectively, after the same period (Table 3-11).

Table 3-11
Expansion Data for Concrete Beams and Slabs Made with Aggregate Po, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)								
			36	*48*	*80*	*91*	*140*	*143*	*195*	*250*	*298*
Po L	***M70***	**Slab Average**	0.008	0.002	-0.006	0.000	-0.003		-0.010	-0.001	0.001
		Average Beams A & B	0.000	-0.005	0.009	-0.004		0.001		0.007	0.005
			34	*46*	*78*	*89*	*138*	*141*	*192*	*248*	*296*
Po	***M62***	**Slab Average**	0.010	0.005	-0.006	0.004	0.004		0.012	0.042	0.067
		Average Beams A & B	0.007	0.001	0.013	0.001		0.006		0.013	0.017
			34	*46*	*89*	*138*	*141*	*192*	*248*	*296*	
Po+	***M63***	**Slab Average**	0.010	0.002	0.001	0.000		0.007	0.037	0.057	
		Average Beams A & B	0.004	-0.001	0.002		0.008		0.013	0.018	
			36	*48*	*91*	*140*	*143*	*195*	*250*	*298*	
Po SF 7.5	***M67***	**Slab Average**	0.017	0.009	0.007	0.006		0.004	0.019	0.026	
		Average Beams A & B	0.011	0.004	0.009		0.013		0.017	0.018	
			36	*48*	*91*	*140*	*143*	*195*	*250*	*298*	
Po SF 7.5+	***M68***	**Slab Average**	0.009	0.000	0.001	-0.002	0.000	-0.001	0.015	0.023	
		Average Beams A & B	0.009	0.001	0.008		0.011		0.014	0.014	
			36	*48*	*91*	*140*	*143*	*195*	*250*	*298*	
Po SF 10+	***M69***	**Slab Average**	0.007	0.001	0.000	0.000		0.002	0.017	0.025	
		Average Beams A & B	0.007	0.005	0.004		0.011		0.015	0.014	
			36	*48*	*80*	*91*	*140*	*143*	*195*	*250*	*298*
Po FA 30+	***M71***	**Slab Average**	0.009	0.000	0.015	-0.005	-0.009		-0.011	0.003	0.006
		Average Beams A & B	0.007	0.002	0.007	-0.004		0.000		0.003	0.003

Concrete Mixture Incorporating Fly Ash

The concrete beams and slab cast from mixture Po FA 30+ (M71) did not show any significant expansion after 6 years of testing outdoors (Table 3-11). The maximum expansion obtained was 0.006%.

Concrete Mixtures Incorporating Silica Fume

None of the concrete beams and slabs incorporating silica fume and the Aggregate Po has expanded excessively after about 300 weeks of testing outdoors; however, trends for increasing expansion were observed for the slab specimens incorporating 7.5% silica fume (Po SF 7.5 – M67 and Po SF 7.5+ - M68) and 10% silica fume (Po SF 10+ – M69) (Table 3-11). The latter has reached average expansions of about 0.025% after about 300 weeks.

Highly-Reactive Aggregate Sp

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slabs incorporating the Aggregate Sp and made with low- and high-alkali cements are given in Table 3-12. The control beams and slab incorporating the low-alkali cement C1 and the aggregate Sp, i.e. Sp L (M26), have not shown any significant expansion after about 310 weeks of testing outdoors. The control beams and slab cast from mixture Sp (M34) and Sp+ (M25) have reached average expansions of 0.084 and 0.135%, and of 0.097 and 0.131%, respectively, after about 310 weeks of outdoor exposure (Table 3-12).

Concrete Mixtures Incorporating Fly Ash

None of the concrete beams and slabs incorporating fly ash and the Aggregate Sp has expanded excessively after 5 to 6 years of testing outdoors (Table 3-12). The average expansions obtained ranged from -0.002 to 0.027%. A trend of increasing expansion was observed, however, for the slab specimen Sp FA 20 (made without added alkalies), which has reached 0.027% expansion after about 300 weeks outdoors.

Concrete Mixtures Incorporating Slag

None of the concrete beams and slabs incorporating slag and the Aggregate Sp has expanded excessively after 6 years of testing outdoors (Table 3-12). The average expansions obtained ranged from -0.001 to 0.023%. A trend of increasing expansion was observed, however, for the slab specimen Sp Sg 35 (made without added alkalies), which has reached 0.023% expansion after 306 weeks.

Table 3-12
Expansion Data for Concrete Beams and Slabs Made with Aggregate Sp, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)								
			51	*59*	*69*	*100*	*112*	*157*	*210*	*262*	*310*
Sp L	***M26***	**Slab Average**	0.001	-0.003	-0.006	0.005	-0.011	-0.007	-0.001	0.000	-0.002
		Average Beams A & B	-0.004	-0.003	-0.013	-0.007	-0.006	-0.004	0.001	0.009	0.009
			49	*57*	*65*	*96*	*108*	*157*	*205*	*257*	*305*
Sp	***M34***	**Slab Average**	0.003	0.004	-0.011	0.016	0.043	0.068	0.078	0.117	0.135
		Average Beams A & B	0.001	0.000	-0.011	-0.003	0.009	0.023	0.050	0.069	0.084
			51	*59*	*69*	*100*	*112*	*157*	*210*	*262*	*310*
Sp+	***M25***	**Slab Average**	0.001	-0.002	-0.014	0.020	0.019	0.043	0.077	0.110	0.131
		Average Beams A & B	0.000	-0.003	-0.018	0.010	0.021	0.040	0.068	0.087	0.097
			35	*38*	*76*	*98*	*147*	*194*	*247*	*295*	
Sp SF 7.5	***M64***	**Slab Average**	0.008	0.002	0.016	-0.001	0.000	0.010	0.010	0.007	
		Average Beams A & B	0.009	0.006	0.014	0.010	0.010	0.017	0.017	0.015	
			35	*45*	*76*	*98*	*147*	*194*	*247*	*295*	
Sp SF 10	***M65***	**Slab Average**	0.010	0.003	0.017	0.004	0.009	0.019	0.016	0.017	
		Average Beams A & B	0.009	0.002	0.016	0.010	0.009	0.015	0.016	0.011	
			48	*76*	*98*	*147*	*194*	*247*	*295*		
Sp SF 10+	***M66***	**Slab Average**	-0.010	0.009	-0.005	-0.001	0.009	0.010	0.009		
		Average Beams A & B	-0.005	0.005	-0.001	0.001	0.003	0.009	0.007		

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)								
			37	*50*	*85*	*100*	*149*	*205*	*248*	*296*	
Sp SF 12.5	***M58***	**Slab Average**	-0.001	-0.002	0.016	0.000	0.002	0.014	0.014	0.012	
		Average Beams A & B	0.010	0.003	0.014	0.009	0.011	0.011	0.017	0.014	
			37	*50*	*85*	*100*	*149*	*197*	*248*	*296*	
Sp FA 20	***M57***	**Slab Average**	0.002	-0.002	0.013	0.002	0.003	0.017	0.026	0.027	
		Average Beams A & B	-0.001	-0.005	0.004	-0.001	0.000	0.012	0.011	0.010	
			45	*58*	*97*	*105*	*152*	*215*	*251*	*299*	
Sp FA 30	***M41***	**Slab Average**	-0.004	-0.004	0.005	-0.006	-0.004	0.005	0.005	0.003	
		Average Beams A & B	-0.004	-0.004	-0.005	-0.002	-0.002	0.007	0.004	-0.002	
			45	*58*	*91*	*105*	*152*	*215*	*251*	*299*	
Sp FA 30+	***M42***	**Slab Average**	-0.017	-0.015	-0.005	-0.015	-0.015	-0.005	-0.001	0.002	
		Average Beams A & B	-0.004	-0.006	-0.007	-0.006	-0.006	0.006	0.001	-0.001	
			44	*58*	*92*	*104*	*119*	*149*	*216*	*253*	
Sp FA 30++	***M44***	**Slab Average**	-0.013	-0.009	-0.001	0.001	-0.015	-0.013	-0.005	0.000	
		Average Beams A & B	-0.003	-0.005	-0.006	-0.006	0.000	-0.006	0.004	0.002	
			50	*57*	*66*	*96*	*110*	*156*	*223*	*258*	*306*
Sp Sg 35	***M30***	**Slab Average**	0.001	0.000	-0.013	0.004	-0.007	-0.001	0.009	0.014	0.023
		Average Beams A & B	-0.002	-0.003	-0.016	-0.008	-0.005	-0.002	0.008	0.007	0.005
			46	*57*	*94*	*107*	*155*	*206*	*257*	*305*	
Sp Sg 50	***M37***	**Slab Average**	0.003	-0.001	0.008	-0.001	0.000	0.007	0.008	0.009	
		Average Beams A & B	-0.002	-0.003	-0.005	-0.005	-0.002	0.006	0.005	0.001	

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)							
			46	*57*	*94*	*107*	*155*	*206*	*257*	*305*
Sp Sg 50+	***M38***	**Slab Average**	0.009	0.004	0.013	0.003	0.004	0.013	0.015	0.018
		Average Beams A & B	0.000	-0.011	-0.005	-0.003	-0.002	0.007	0.006	0.002
			42	*55*	*90*	*101*	*146*	*198*	*250*	*298*
Sp Sg 50++	***M45***	**Slab Average**	-0.005	-0.009	0.006	-0.006	-0.004	0.006	0.010	0.013
		Average Beams A & B	-0.003	-0.005	-0.007	-0.007	-0.005	0.005	0.003	0.000
			42	*55*	*90*	*101*	*146*	*198*	*250*	*298*
Sp Sg 65	***M46***	**Slab Average**	-0.003	-0.006	0.010	-0.004	0.004	0.011	0.012	0.014
		Average Beams A & B	-0.009	-0.008	-0.009	-0.011	-0.006	0.001	0.001	-0.001

Concrete Mixtures Incorporating Silica Fume

None of the concrete beams and slabs incorporating silica fume and the Aggregate Sp has expanded significantly after about 300 weeks of testing outdoors (Table 3-12). The average expansions obtained ranged from 0.007 to 0.017%

Highly-Reactive Aggregate Con

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slabs incorporating the Aggregate Con, and made with low- and high-alkali cements, are given in Table 3-13. The control beams and slab incorporating the low-alkali cement C1 and the aggregate Con, i.e. Con L (M87), have not shown any significant expansion after 213 weeks of outdoor exposure. The control beams and slab from mixture Con (M85) have reached average expansions of 0.046 and 0.070%, respectively, after 213 weeks outdoors; the expansions reached by the control beams and slab Con+ made with added alkalies, were 0.043 and 0.063%, respectively, after 204 weeks outdoor (Table 3-13).

Concrete Mixtures Incorporating Fly Ash

None of the concrete beams and slabs incorporating fly ash and the Aggregate Con has expanded excessively after 4 years of testing outdoor (Table 3-13). However, a trend of increasing expansion was observed for the slab specimens Con FA 20+ (M89) and Con FA 30+++ (M99), which has reached 0.026 and 0.023% expansion, respectively, after about 200 weeks outdoors (Table 3-13).

Table 3-13
Expansion Data for Concrete Beams and Slabs Made with Aggregate Con, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)				
			54	*115*	*165*	*213*	
Con L	***M87***	**Slab Average**	0.003	0.006	0.003	0.000	
		Average Beams A & B	-0.003	0.002	0.002	-0.003	
			54	*115*	*165*	*213*	
Con	***M85***	**Slab Average**	-0.008	0.009	0.037	0.070	
		Average Beams A & B	0.001	0.003	0.024	0.046	
			53	*55*	*106*	*156*	*204*
Con+	***M86***	**Slab Average**	0.005		0.015	0.042	0.063
		Average Beams A & B	0.003	0.000	0.007	0.027	0.043
			52	*54*	*104*	*159*	*207*
Con FA 20	***M88***	**Slab Average**	-0.014		-0.001	0.004	0.012
		Average Beams A & B	-0.006	-0.010	-0.007	-0.002	0.001
			52	*54*	*104*	*159*	*207*
Con FA 20+	***M89***	**Slab Average**	-0.014		0.004	0.015	0.026
		Average Beams A & B	-0.007	-0.011	-0.009	0.000	0.004
			52	*54*	*104*	*154*	*202*
Con FA 30	***M90***	**Slab Average**	-0.014		-0.002	0.000	0.002
		Average Beams A & B	-0.003	-0.007	-0.006	-0.001	0.000
			52	*54*	*104*	*154*	*202*
Con FA 30+	***M91***	**Slab Average**	-0.016		0.000	0.002	0.008
		Average Beams A & B	-0.005	-0.008	-0.007	-0.001	0.001
			48		*96*	*147*	*195*
Con FA 30+++	***M99***	**Slab Average**	-0.005		0.010	0.015	0.023
		Average Beams A & B	0.005		-0.001	0.007	0.011
			52	*54*	*103*	*154*	*202*
Con FA 56	***M92***	**Slab Average**	-0.014		0.000	-0.001	-0.003
		Average Beams A & B	-0.011	-0.012	-0.013	-0.008	-0.007
			52	*54*	*103*	*154*	*202*
Con FA 56+	***M93***	**Slab Average**	-0.015		-0.005	-0.006	-0.008
		Average Beams A & B	-0.009	-0.013	-0.012	-0.007	-0.006

Highly-Reactive Aggregate Sl

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slabs incorporating the Aggregate Sl, and made with low- and high-alkali cements, are given in Table 3-14. The control beams and slab incorporating the low-alkali cement C1 and the aggregate Sl, i.e. Sl L (M1), have not shown any significant expansion after about 350 weeks of outdoor exposure. The control beams and slab cast from mixture Sl (M2) have reached average expansions of 0.224 and 0.326%, respectively, after 350 weeks of outdoor exposure; the expansions reached by the control beams and slab Sl+ (M3) made with added alkalies, were 0.229 and 0.338%, respectively, at the same age (Table 3-14).

Concrete Mixtures Incorporating Fly Ash

Expansions in excess of the 0.04% level were measured on concrete beams and slabs incorporating 20% fly ash, after 6 years of testing outdoors (Table 3-14). The average expansions obtained were 0.022 and 0.047%, respectively, for the specimens Sl FA 20, and 0.048 and 0.072%, respectively, for the specimens Sl FA 20+. A trend of increasing expansion was also observed for the beam specimen Sl FA 30+, which has reached 0.022% average expansion after 311 weeks outdoor.

Concrete Mixtures Incorporating Silica Fume

Expansions in excess of the 0.04% level were measured on concrete beams and slabs incorporating 7.5% silica fume after 7 years of testing outdoors (Table 3-14). The average expansions obtained were 0.035 and 0.065% for the specimens Sl SF 7.5+. A trend of increasing expansion was also observed for the slab and beam specimens Sl SF 10+, all of which have reached 0.023% average expansion after 350 weeks outdoor.

Table 3-14
Expansion Data for Concrete Beams and Slabs Made with Aggregate SI, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)											
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI L	***M1***	**Slab Average**	0.000	-0.001	-0.005	-0.002	-0.001	-0.005	0.005	-0.009	-0.003	-0.007	-0.006	-0.005
		Average Beam A & B	0.000	-0.001	-0.008	-0.002	-0.001	-0.007	-0.006	0.005	0.004	0.011	0.014	0.016
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI	***M2***	**Slab Average**	-0.004	-0.001	-0.003	0.002	0.002	-0.004	0.029	0.054	0.116	0.204	0.276	0.326
		Average Beam A & B	-0.001	-0.001	-0.008	-0.001	0.000	-0.008	0.000	0.026	0.049	0.108	0.177	0.224
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI +	***M3***	**Slab Average**	-0.005	-0.002	-0.007	0.003	0.004	-0.002	0.066	0.090	0.140	0.203	0.276	0.338
		Average Beam A & B	-0.002	0.000	-0.009	0.001	0.003	-0.009	0.023	0.061	0.093	0.148	0.195	0.229
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI SF 7.5	***M4***	**Slab Average**	-0.002	-0.002	-0.002	-0.003	-0.001	-0.007	0.002	-0.003	-0.001	0.003	0.006	0.008
		Average Beam A & B	0.002	0.001	-0.007	-0.001	0.002	-0.010	-0.007	0.008	0.004	0.016	0.017	0.020
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI SF 7.5+	***M7***	**Slab Average**	-0.010	-0.008	-0.009	-0.005	-0.005	-0.012	0.005	0.000	0.006	0.019	0.044	0.065
		Average Beam A & B	0.000	0.000	-0.007	-0.002	0.000	-0.006	-0.007	0.009	0.006	0.021	0.026	0.035
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI SF 10	***M5***	**Slab Average**	-0.009	-0.006	-0.008	-0.002	-0.002	-0.016	0.002	-0.003	-0.003	0.001	0.003	0.004
		Average Beam A & B	-0.003	-0.004	-0.010	-0.004	-0.003	-0.012	-0.009	0.006	0.001	0.013	0.013	0.015
			35	*43*	*54*	*92*	*101*	*110*	*140*	*153*	*197*	*249*	*302*	*350*
SI SF 10+	***M6***	**Slab Average**	-0.004	-0.002	-0.006	0.000	0.001	-0.006	0.008	0.004	0.004	0.010	0.016	0.023
		Average Beam A & B	0.001	0.000	-0.006	0.000	0.000	-0.005	-0.005	0.010	0.007	0.018	0.019	0.023

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)											
			30	*41*	*48*	*88*	*96*	*105*	*136*	*149*	*193*	*245*	*302*	*350*
SI SF 12.5	***M8***	**Slab Average**	0.000	-0.005	-0.013	-0.017	-0.011	-0.027	-0.009	-0.009	-0.007	0.001	0.001	0.002
		Average Beam A & B	0.003	0.003	-0.003	0.002	0.003	-0.005	-0.003	0.012	0.006	0.019	0.018	0.019
			30	*41*	*48*	*88*	*96*	*105*	*136*	*149*	*193*	*245*	*302*	*350*
SI SF 12.5+	***M9***	**Slab Average**	0.001	0.000	-0.001	-0.007	-0.001	-0.005	0.009	0.009	0.006	0.003	0.013	0.016
		Average Beam A & B	0.002	0.002	-0.003	0.003	0.004	-0.003	-0.002	0.011	0.009	0.021	0.021	0.024
			52	*62*	*70*	*104*	*114*	*158*	*211*	*263*	*311*			
SI FA 20	***M19***	**Slab Average**	-0.009	-0.004	-0.020	-0.002	-0.003	0.005	0.015	0.035	0.047			
		Average Beam A & B	-0.010	-0.006	-0.017	-0.014	-0.003	-0.005	0.009	0.013	0.022			
			52	*62*	*70*	*104*	*114*	*158*	*211*	*263*	*311*			
SI FA 20+	***M20***	**Slab Average**				0.013	-0.004	0.003	0.000	0.049	0.072			
		Average Beam A & B	-0.005	-0.001	-0.024	-0.010	0.001	0.003	0.024	0.035	0.048			
			52	*62*	*70*	*104*	*114*	*158*	*211*	*263*	*311*			
SI FA 30	***M21***	**Slab Average**	0.003	0.005	-0.016	-0.003	-0.005	-0.003	0.004	0.011	0.016			
		Average Beam A & B	-0.006	-0.003	-0.015	-0.011	-0.005	-0.007	0.005	0.004	0.008			
			52	*62*	*70*	*104*	*114*	*158*	*211*	*263*	*311*			
SI FA 30+	***M22***	**Slab Average**	0.002	0.006	-0.019	-0.002	-0.003	0.003	0.016	-0.001	0.013			
		Average Beam A & B	-0.005	0.000	-0.021	-0.010	-0.004	-0.003	0.011	0.015	0.022			
			52	*62*	*70*	*104*	*114*	*158*	*211*	*263*	*311*			
SI FA 56	***M23***	**Slab Average**	-0.017	-0.010	-0.035	-0.020	-0.026	-0.021	-0.019	-0.016	-0.014			
		Average Beam A & B	-0.014	-0.011	-0.030	-0.020	-0.014	-0.018	-0.010	-0.012	-0.010			
			52	*62*	*70*	*104*	*114*	*158*	*211*	*263*	*311*			
SI FA 56+	***M24***	**Slab Average**	-0.011	-0.005	-0.031	-0.016	-0.021	-0.018	-0.012	-0.013	-0.010			
		Average Beam A & B	-0.017	-0.013	-0.033	-0.022	-0.016	-0.019	-0.011	-0.012	-0.010			

Highly-Reactive Aggregate NM

Control Concrete Mixtures Incorporating Low and High-Alkali Cements

The average expansions reached to date for the control concrete beams and slab made with the high-alkali cement and the Aggregate NM are given in Table 3-15. The control beams and slab NM (M111) have reached average expansions of 0.243 and 0.279%, respectively, after about 200 weeks outdoors (Table 3-15).

Concrete Mixtures Incorporating Fly Ash

None of the concrete beams and slabs incorporating fly ash and the Aggregate NM has expanded excessively after 2 years of testing outdoors (Table 3-15). The expansions ranged from 0.002 to 0.015% after about 90 weeks outdoors.

Table 3-15
Expansion Data for Concrete Blocks and Slabs Made with Aggregate NM, and Exposed Outdoors at CANMET Site in Ottawa, Canada

Mixture Designation		Specimens	Expansion (%) Against Time (Weeks)			
			89	*93*	*142*	*191*
NM	***M111***	**Slab Average**	0.111		0.206	0.279
		Average Beams A & B		0.103	0.182	0.243
			42	*89*		
NM FA 20+	***M160***	**Slab Average**	0.000			
		Average Beams A & B	0.007	0.015		
			42	*89*		
NM FA 30+	***M161***	**Slab Average**	-0.013	0.006		
		Average Beams A & B	-0.005	0.002		

Alkali-Aggregate Reactivity Testing in the Laboratory – Length Changes in Mortar Bar

General Comments on the Use of the Accelerated Mortar Bar Test

The maximum 14-day expansion limit for non-reactive aggregate ranges somewhere between 0.08 and 0.20%, with a value of 0.15% appearing generally applicable. Effectively, according to the Appendix B of CSA A23.1-00 [6], an aggregate is to be considered potentially alkali-reactive if it produces an expansion > 0.15% (0.10% for siliceous limestones) after 14 days in the CSA A23.2-25A [4] (equivalent to ASTM C 1260 [5]) Accelerated Mortar Bar Test (AMBT).

In the case of evaluating the effectiveness of SCMs to conteract ASR expansion, the standard practice CSA A23.2-28A [8] states that: "*The materials to be evaluated shall be tested for two years according to CSA Test Method A23.2-14A or, if sufficient time is not available, for 14 day according to CSA Test Method A23.2-25A. When decisions are based on the results obtained from CSA Test Method A23.2-25A, a program of testing to validate those results shall be started using CSA Test Method A23.2-14A at the same time. In cases of disagreement between the two tests, the results obtained using CSA Test Method A23.2-14A shall govern in the absence of satisfactory documented field performance*". A number of researchers have found that the AMBT, using an expansion limit of 0.10% at 14 days, can effectively give a good indication of the effectiveness of SCM in controlling expansion due to ASR [9-13].

Accelerated mortar bar expansions obtained for the different aggregates used in the study are summarized in Tables 3-16 to 3-23.

Control Mortar Mixtures with High-Alkali Cements

The use of a 0.15% expansion limit at 14 days has permitted to identify the potential alkali-silica reactivity of most reactive aggregates investigated in this study. The 14-day expansions of control mortars ranged from 0.093% (aggregate Po) to 0.854% (aggregate NM) (Tables 3-16 to 3-23).

Because of its special compositional and textural characteristics, the Potsdam sandstone (aggregate Po) produced a limited 14-day expansion of 0.093% (Table 3-19). The special behaviour of siliceous sandstones, such as the Potsdam aggregate, in the accelerated mortar bar test has been identified in the Appendix B of CSA Standard A23.1-00 [6].

Fly Ash Mortar Mixtures

The use of fly ash contributed in significantly reducing the expansion of mortar bars incorporating the different reactive aggregates used in this study. Decreasing mortar bar expansion was always obtained with increasing fly ash content in the mortar mixture.

Mortar bars incorporating 30 or 56% ASTM Class F (or low-calcium) fly ash and the various reactive aggregates tested consistently met the proposed 0.10% expansion limit. This suggests thus suggesting that such replacement levels would represent an adequate protection against deleterious expansion for the different moderate- to highly-reactive aggregates investigated.

The effectiveness of the 20% fly ash system was found to vary according to the aggregate investigated and/or the fly ash used. Mortar bar expansions in excess of 0.10% at 14 days were obtained with the highly-reactive Sp aggregate (0.103%; Sp FA 20 – Table 3-20), Con aggregate (0.175%; Con FA 20 – Table 3-21) and NM aggregate (0.375%; NM FA 20 – Table 3-23).

Slag Mortar Mixtures

As observed with fly ash, the use of slag, especially at large quantities, contributed in significantly reducing the expansion of mortar bars incorporating the reactive aggregates Su and Sp. Decreasing mortar bar expansion was always obtained with increasing slag content in the mortar mixture.

Mortar bars incorporating 50 or 65% slag consistently met the proposed 14-day 0.10% expansion limit, thus suggesting that such replacement levels would represent an adequate protection against deleterious expansion for the different moderate- to highly-reactive aggregates investigated. The use of 35% slag did not result in sufficient reduction in expansion of mortar bars incorporating the moderately-reactive Su aggregate (0.140; Su Sg 35 – Table 3-16) and the highly-reactive Sp aggregate (0.190%; Sp Sg 35 – Table 3-20).

Silica Fume Mortar Mixtures

The use of silica fume contributed to reducing expansion of mortar bars incorporating the different reactive aggregates used. Decreasing mortar bar expansion was always obtained with increasing silica fume content in the mortar mixture.

Mortar bars incorporating 12.5% silica fume invariably met the proposed 0.10% expansion limit thus suggesting that such replacement levels would represent an adequate protection against deleterious expansion for the different moderately- to highly-reactive aggregates investigated.

The effectiveness of the 7.5 and 10% silica fume systems was found to vary according to the aggregate investigated. Mortar bar expansions in excess of 0.10% at 14 days were obtained for the following mortar mixtures:

- 7.5% SF mixture incorporating the Su aggregate (0.112% for Su SF 7.5; Table 3-16)
- 7.5% and 10% SF mixtures incorporating the Sp aggregate (0.180% for Sp SF 7.5 and 0.142% for Sp SF 10; Table 3-20),
- 7.5% and 10% SF mixtures incorporating the Sl aggregate (0.130% for Sl SF 7.5 and 0.120% for Sl SF 10; Table 3-22).

Table 3-16
Expansion Data for Mortar bars Incorporating Aggregate Su

Mixture Designation	Expansion (%) against Time (days)							
	1	4	7	10	12	14	21	28
Su	0.007	0.050	0.127	0.198	0.241	0.278	0.387	0.464
Su FA 20	0.005	0.014	0.024	0.031	0.037	0.048	0.087	0.125
Su FA 30	0.001	0.008	0.012	0.015	0.015	0.021	0.032	0.040
Su FA 56	0.001	0.001	0.003	0.004	0.000	0.005	0.011	0.010
Su Sg 35	0.008	0.032	0.056	0.097	0.116	0.140	0.203	0.259
Su Sg 50	0.009	0.016	0.013	0.032	0.035	0.043	0.070	0.098
Su Sg 65	0.003	0.002	0.001	0.011	0.008	0.019	0.023	0.034
Su SF 7.5	0.010	0.022	0.037	0.059	0.084	0.112	0.201	0.282
Su SF 10	0.010	0.019	0.030	0.042	0.054	0.078	0.158	0.225
Su SF 12.5	0.005	0.018	0.026	0.036	0.045	0.052	0.123	0.182

Table 3-17
Expansion Data for Mortar bars Incorporating Aggregate A1

Mixture Designation	Expansion (%) against Time (days)							
	1	3	7	10	12	14	21	28
Al	0.007	0.074	0.201	0.276	0.323	0.360	0.489	0.587
Al FA 20	-0.002	0.011	0.021	0.028	0.035	0.037	0.054	0.067
Al FA 30	-0.002	0.003	0.012	0.017	0.025	0.026	0.033	0.041
Al FA 56	0.004	0.004	0.009	0.014	...	0.029	0.025	0.023
Al SF 7.5	-0.001	0.013	0.037	0.052	0.073	0.090	0.160	0.222
Al SF 10	0.008	0.016	0.030	0.041	0.054	0.068	0.125	0.177
Al SF 12.5	0.001	0.020	0.037	0.050	0.063	0.072	0.117	0.160

Table 3-18
Expansion Data for Mortar bars Incorporating Aggregate Wy

Mixture	Expansion (%) against Time (days)							
Designation	1	3	7	10	12	14	21	28
Wy	0.015	0.087	0.172	0.208	0.218	0.231	0.278	0.322
Wy FA 20	Not available							
Wy FA 30	Not available							

Table 3-19
Expansion Data for Mortar bars Incorporating Aggregate Po

Mixture	Expansion (%) against Time (days)							
Designation	1	4	7	11	14	18	21	28
Po	0.002	0.021	0.051	0.073	0.093	0.118	0.139	0.193

Table 3-20
Expansion Data for Mortar bars Incorporating Aggregate Sp

Mixture	Expansion (%) against Time (days)							
Designation	1	4	7	10	12	14	21	28
Sp	0.020	0.143	0.263	0.327	0.364	0.391	0.503	0.617
Sp FA 20	0.012	0.029	0.058	0.076	0.095	0.103	0.160	0.242
Sp FA 30	0.009	0.014	0.029	0.032	0.039	0.032	0.059	0.116
Sp FA 56	0.011	0.006	0.018	0.014	0.020	0.008	0.006	0.023
Sp Sg 35	0.017	0.064	0.131	0.161	0.180	0.190	0.258	0.351
Sp Sg 50	0.016	0.021	0.041	0.048	0.059	0.066	0.112	0.181
Sp Sg 65	0.010	0.007	0.023	0.022	0.027	0.017	0.041	0.096
Sp SF 7.5	0.014	0.032	0.084	0.126	0.157	0.180	0.301	0.473
Sp SF 10	0.020	0.034	0.060	0.097	0.123	0.142	0.246	0.402
Sp SF 12.5	0.016	0.023	0.045	0.054	0.073	0.087	0.177	0.309

Table 3-21
Expansion Data for Mortar bars Incorporating Aggregate Con

Mixture	Expansion (%) against Time (days)						
Designation	1	4	7	11	14	21	28
Con	0.008	0.121	0.231	0.346	0.419	0.524	0.603
Con FA 20	0.005	0.045	0.083	0.137	0.175	0.228	0.271
Con FA 30	0.001	0.010	0.024	0.040	0.062	0.075	0.091

Table 3-22
Expansion Data for Mortar bars Incorporating Springhill Aggregate (SI)

Mixture	Expansion (%) against Time (days)							
Designation	1	4	7	9	12	14	21	28
SI	0.019	0.139	0.312	0.367	0.435	0.463	0.598	0.700
SI FA 20	0.013	0.037	0.047	0.051	0.069	0.065	0.116	0.137
SI FA 30	0.004	0.016	0.023	0.022	0.030	0.034	0.035	0.036
SI FA 56	-0.001	0.004	0.005	0.006	0.014	0.014	0.017	0.011
SI SF 7.5	0.012	0.028	0.044	0.064	0.100	0.130	0.208	0.276
SI SF 10	...	0.024	0.035	0.051	0.098	0.120	0.206	0.284
SI SF 12.5	0.008	0.025	0.036	0.038	0.045	0.040	0.111	0.159

Table 3-23
Expansion Data for Mortar bars Incorporating Aggregate NM

Mixture	Expansion (%) against Time (days)							
Designation	1	3	7	10	12	14	21	28
NM	0.135	0.413	0.668	…	0.808	0.854	0.961	1.04
NM FA 20	0.028	0.276	0.299	…	0.382	0.395	0.437	0.461
NM FA 30	0.004	0.013	0.029	…	0.067	0.088	0.117	0.141

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4

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 a number of factors, including the chemical composition of the SCM and the potential alkali-reactivity of the aggregates.

In the case of the three moderately-reactive aggregates and SCMs used and tested in this study, i.e. aggregates that induced an expansion between 0.04 and 0.12% at one year in the Concrete Prism Test (CSA A23.2-14A or ASTM C 1293), laboratory test data indicated that the use of either 20% and more ASTM Class F fly ash, 35% and more ground granulated blastfurnace slag, or 7.5% and more silica fume, could be sufficient to control deleterious expansion due to ASR. The above conclusions were confirmed by the data obtained to date on companion specimens subjected to outdoor exposure at CANMET site in Ottawa. Monitoring of concrete beams and slabs is still being continued to confirm the long-term performance of the various concrete mixtures under test.

In the case of the five highly-reactive aggregates and SCMs used and tested in this study, i.e. for aggregates that induced an expansion > 0.12% at one year in the Concrete Prism Test (CSA A23.2-14A or ASTM C 1293), laboratory test data indicated that larger amounts of SCMs are required (i.e. compared to moderately-reactive aggregates) to adequately control ASR expansion.

- In the case of ASTM Class F fly ash, the minimum replacement amounts required will vary according to the nature of the fly ash and the reactivity level of the aggregate; however, a minimum replacement level of 30% seems to be generally apply, with maybe, the exception of extremely reactive aggregates such as the aggregate NM.
- In the case of ground granulated blast furnace slag, laboratory test data suggest that the minimum replacement amount required lies between 35 and 50%, depending on the reactivity level of the aggregate.
- In the case of silica fume, laboratory test data suggest that more than 10% replacement level would be required to control ASR expansion with highly-reactive aggregates.

The above conclusions were drawn on the basis of laboratory tests using reactive aggregates showing a range of reactivity levels and petrological characteristics, in addition to using SCMs of various types and compositions. These are general conclusions that may not apply in every circumstances. Additional testing may be necessary to confirm the performance of specific combinations of reactive aggregates and SCMs.

The data obtained to date for companion specimens subjected to outdoor exposure, at CANMET site in Ottawa, generally confirm the test data obtained in the laboratory. Monitoring of concrete beams and slabs is still being carried out to confirm the long-term performance of the various concrete mixtures under test.

With only a few exceptions, the accelerated mortar bar test, using an expansion limit of 0.10% at 14 days, generally gives a good indication of the effectiveness of SCMs in controlling expansion due to ASR. Accelerated mortar bar test (AMBT) data suggest that the use of 30% and more ASTM Class F fly ash, 50% and more slag or 12.5% silica fume would represent an adequate protection against deleterious expansion for most of the different moderate- to highly-reactive aggregates investigated. AMBT data also suggest that the use of the above supplementary cementing materials at lower replacement levels, i.e. 20% fly ash, or 7.5 to 10% silica fume, could be effective in controlling expansion caused by some moderately-reactive aggregates.

Target:
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