EFFECT OF ENVIRONMENTAL CONDITIONS ON EXPANSION IN CONCRETE DUE TO ALKALI-SILICA REACTION (ASR)

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Abstract

The environmental conditions to which a concrete element incorporating alkali-silica reactive aggregates is exposed play a major role in dictating the progression and manifestation of the reaction. This paper reports and analyses the results of research programs investigating the comparative evaluation of the effect of environmental conditions on the development of alkali-silica reaction (ASR) in concrete specimens stored in outdoor exposure at the authors' respective laboratories. This data is compared to samples subjected to laboratory testing (controlled environmental conditions). Concrete mixtures that incorporate reactive aggregates with varying reactivity levels are compared.. The focus of this paper is on control concretes e.g. 100% opc + reactive aggregate (coarse or fine).

Keywords: field exposure, laboratory testing, reactive aggregate and environmental effects

1 INTRODUCTION

While laboratory testing methods to assess susceptibility to alkali-silica reaction aim to provide a controlled testing environment to produce accurate and reliable results, they do not capture the environmental effects to which real concrete structures are subjected. Certainly laboratory testing methods are essential evaluation tools for alkali-silica reactivity and extensive outdoor field exposure testing is beyond the time frame for many research programs. However, it is important to ensure that results of laboratory testing predict alkali-silica reactivity in real field exposure and that we continue to work toward improving the accuracy and reliability of laboratory testing methods through comparison to field exposed concrete. In an effort to provide this type of comparison, the authors are involved in extensive comparative field and laboratory testing for evaluating the alkali-silica reactivity of a wide variety of reactive aggregate types from across North America in a variety of testing environments.

This paper presents the results of expansion testing performed in the laboratory on concrete prisms (CSA A23.2-14A or ASTM C 1293 methods) and mortar bars (CSA A23.2-25A or ASTM C 1260) incorporating a variety of moderately to highly-reactive aggregates, and compares the above results to the field performance of concrete blocks incorporating the same aggregates but exposed outdoors on two different sites located in Canada and in the USA. The results are analysed in view of the different exposure / climatic conditions to which the specimens are subjected.

2 MATERIALS AND METHODS

2.1 General

For the past several years, extensive ASR investigations were conducted by the authors, through which a series of aggregates of different types and origins (geographical location) were tested both at The University of Texas at Austin, USA (UT) and at CANMET in Ottawa, Canada (Figure 1). As part of the various collaborative projects carried out at both locations, large concrete mixtures (~0.18-0.40 m^3) were commonly made in the laboratory which enabled concrete test prisms and cylinders (laboratory exposure) as well as larger-size outdoor exposure blocks to be cast from the same mixture (Figure 2). Such a practice not only provides critical data for the validation of laboratory test procedures, but allows for the comparative evaluation of the effect of testing/exposure conditions on the development of expansion due to ASR. Data from on-going field and laboratory investigations performed at UT and CANMET were presented separately [1,2].

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2.2 Materials and mix designs

Table 1 shows the type, source and brief petrographic descriptions of the coarse and fine aggregates for which test results are reported in this paper. About 5-6 tons of the above aggregates were sampled by the producers from various stockpiles (size fractions 5 to 25 mm) in the quarried or sand/gravel operations selected; the materials were then shipped to Texas and Ottawa for further processing and testing. In the case of the reactive Sp and Su aggregates, materials were obtained from reference stockpiles stored at the Ontario Ministry of Transportation premises in Toronto, Canada.

High-alkali ASTM Type I (or CSA Type 10) portland cements from the USA (used in Texas) and Canada (used at CANMET) were obtained for testing. Chemical compositions of these cements are shown in Table 2. Concrete mixtures were made following the mixture proportioning requirements of ASTM C 1293 (mixtures made at UT) and CSA A23.2-14A (mixtures made at CANMET). Both methods request the use of a nominal cementitious materials content of 420 ± 10 kg/m^3 and awater-to-cement ratio within the range of 0.42 to 0.45. The CSA and ASTM methods however differ as the ASTM method specifies the use of a coarse aggregate oven-dry-rodded unit volume of 70± 2% for all classes of coarse aggregates, while the CSA method uses a fixed coarse-to-fine aggregate ratio of 60:40, by mass, for normal density aggregates. The above difference has a definite impact on the aggregate contents in the mixtures, as illustrated in the two examples shown in Table 3.

For comparison purposes, concrete mixtures were made with (boosted) and without added alkalis (unboosted); for mixtures with added alkalis, reagent grade NaOH was added to increase the alkali content to 1.25% (Na_2O_{eq}), per cement mass. Air-entraining admixtures were used in all concrete mixtures made at CANMET and in a selected number of mixtures made at UT; non air-entrained concrete mixtures were also made at UT. The target air content was 6 ± 1% for all air-entrained concrete mixtures.

2.3 Casting and testing of the concrete specimens

Concrete prisms measuring 75 by 75 by 250-300 mm were cast from each mixture for laboratory evaluation. After 24 ± 0.5 hours the test prisms were demolded and measured (initial length and weight), placed in appropriate containers and then stored in a walk-in chamber at 38 ± 1.5°C. Length-change measurements were performed at regular intervals over a two year period.

At both laboratories, concrete blocks measuring 0.40 by 0.40 by 0.70 m in size, were cast from the same mixtures as the concrete prisms described above. The blocks were kept in molds covered with wet burlap for seven days after casting. At this point the blocks were demolded and an initial length at 23 ± 2 °C was recorded. Length measurements were taken on the longitudinal and transverse axis on the top of the blocks, and in the longitudinal direction on both sides of the block (e.g. Figure 2B). Length measurements are taken between eight (CANMET) and twelve (UT) points on the exposure blocks, resulting in six or eight total measurements, respectively. These measurement points are created by casting 9.5 mm (diameter) by 76 mm (length) threaded rods into the fresh concrete. These bolts have a machined "demec point" at the exposed end. After the initial measurement, blocks were placed in the respective laboratories' outdoor exposure site directly on compacted gravel material (0-20mm) (Figure 2).

At CANMET, concrete blocks were cast, placed outdoors and length-change measurements taken between May and early November of each year. At UT, concrete blocks were cast, placed outdoors and monitored for length changes year-round. At both locations, length-change measurements are carried out when the temperature is 23°C ± 2°C and the weather is mostly cloudy. Additionally, a non-reactive control block is measured periodically throughout one measurement period to detect any expansion due to thermal effects, at which time measuring would cease until temperatures were again favourable. Due to the high summer temperatures and an average of 300 of 365 days a year of sun in Austin, Texas, block measuring at UT is sporadic and often limited to only a few hours in the early morning especially during the summer months.

In 2003, companion sets of concrete blocks containing selected reactive aggregate (highly-reactive sand (Jb), Spratt limestone (Sp) and Sudbury gravel (Su)) were made at CANMET (6 blocks total, 2 from each aggregate source). One block from each set was shipped to Texas for outdoor exposure testing while the other was placed on the CANMET site for comparative length-change monitoring. This "exchange series" was done to isolate the effect of the exposure conditions on ASR expansion with concrete cast from exactly the same mixture. The concrete mixtures were made in accordance with CSA requirements, as described in the previous sections.

2.4 Weather conditions

Figure 3 illustrates yearly average temperature (4A) and precipitation (4B) at Austin and Ottawa. Differences in climatic condition sbetween Austin and Ottawa provide an ideal opportunity to study the effect of the exposure conditions on expansion due to ASR in concrete specimens incorporating "common" reactive aggregates..

3 RESULTS

3.1 Effect of the exposure conditions on block expansions

Table 4 shows the expansion data of the exposure blocks that were made as part of the exchange series (section 2.4 above). After three years of outdoor exposure, the difference in expansions between the two sites increases with decreasing aggregate reactivity level (Figure 4). In the case of the highly-reactive Jb sand, the companion block stored in Texas experienced about 50% more expansion (0.365% vs 0.557%), while the difference is roughly 750% in the case of the less reactive Su gravel (Table 4); the significant difference in the latter case is because expansion has not begun in the companion block stored in Ottawa. Figure 5 shows that, in the case of the reactive Jb and Sp aggregates, the expansion rates of the blocks between the two sites seem to be fairly similar, especially after significant expansion has started in the blocks at both sites.

Table 5 shows the expansion data obtained to date for the exposure blocks, with/without added alkalis and air entrainment; blocks of the CAN series were made and tested at CANMET, while those of the UT series were made and tested at The University of Texas at Austin. Figure 6 compares the expansion after three or four years for exposure blocks stored on the two sites. Data are shown for the same aggregates used in boosted blocks (marked with a "+", e.g. Wt+). Although block expansions are generally significantly higher in Texas, the data suggest that the response to the differences in exposure conditions varies from one aggregate to another. This can also be seen in the expansion curves illustrated on Figure 7. For instance, while exposure blocks made with Wt and Su aggregates have not expanded significantly on the CANMET site (<0.03%), the "corresponding" blocks stored in Texas expanded and cracked extensively (0.508% at 3 years for Wt; 0.203% at 4 years for Su). On the other hand, although expansion started slowly for the NM+ block stored in Ottawa, the 3-year expansions in blocks made this aggregate were not significantly different for blocks stored at CANMET (0.265%) and Texas (0.319%).

3.2 Effect of the concrete alkali content and air entrainment on block expansions

Figure 8 shows a plot of the expansion of boosted and unboosted concrete blocks stored in Texas (non air-entrained blocks) and in Ottawa (air-entrained blocks). Figures 9 and 10 illustrate curves of expansion of unboosted and boosted blocks. The above figures and the data in Table 5 show that exposure block expansions are affected by the addition of alkalis to the concrete, however the effects vary based on aggregate type. The expansion of blocks incorporating the Minn aggregate and stored in Texas are fairly sensitive to alkali boosting as seen in Figures 8 and 10; the corresponding blocks in Ottawa have however not expanded significantly even after 7 years of outdoor exposure. Similarly, the unboosted NM blocks, (CAN IC1 and CAN M111), expanded by about 0.200% after three years while the corresponding boosted block, NM+ (CAN IC4), expanded by 0.265% (Figure 8 and 9); despite the faster onset of expansion observed with the boosted block NM+, the expansion curves of the boosted and unboosted blocks were however fairly similar (Figure 9). On the other hand, while the expansion of the boosted and unboosted concrete blocks incorporating the aggregates Su and Sp seem to be fairly similar on the Ottawa site, the difference in expansion of similar (i.e. boosted vs unboosted) blocks is more significant on the Texas site (Figures 9 and 10).

The potential beneficial effect of air entrainment at reducing expansion in concrete incorporating reactive aggregates has been mentioned in the literature [3], as air voids could provide space, to at least temporarily, accommodate generated alkali-silica gel. Pleau et al. [4] however found that the use of air-entrainment had little effect on the expansion of concrete prisms incorporating the highly-reactive Spratt limestone. Figure 11 shows a plot of the effect of air entrainment on the expansion of exposure blocks stored on the Texas outdoor exposure site. The results indicate that the use of air-entrainment does not have a clear effect on expansion due to ASR; air-entrained blocks incorporating the aggregates NM, Sp, Su Vir and Penn expanded slightly more than un-air-entrained concretes while the opposite was observed for the blocks made with the reactive aggregatges Minn, Wy and Wt. The exact reason for such a difference in performance is still uncertain and merits further investigations.

3.3 Expansion in concrete prisms

Table 6 shows the expansion of the concrete prisms cast from the same mixtures from which concrete blocks were made, and were stored for a one-year period at 38 ± 2°C and R.H. > 95%. As expected, the addition of alkalis to the concrete resulted in significant increase in concrete prism expansion for most aggregates, as illustrated in Figure 12.

4 DISCUSSION

Over the years, many studies have confirmed that concrete prism testing is the most reliable method for evaluating potential alkali-reactivity of concrete aggregates, while accelerated mortar bar testing can result in the rejection of aggregates with acceptable field performance or the acceptance of potentially deleterious aggregates. Both CSA and ASTM concrete prism tests require that the concrete alkalis be boosted to 1.25% Na_2O_{eq}, by cement mass, for the evaluation of the potential alkali-silica reactivity of concrete aggregates. The data in Figure 12 show that some concrete prisms without added alkalis indeed experienced expansion lower or close to the 0.040% expansion limit at one year (e.g. Minn, Su, Penn), while all boosted prisms expanded significantly over the limit thus confirming the deleterious character of the aggregates tested. The differences in expansion observed between CANMET and UT are attributed to the use of different test methods (CSA and ASTM, cements, non-reactive aggregates, etc.). Previous inter-laboratory testing programs had showed that, for test prisms made in the same laboratory, concrete prism expansions measured at CANMET and UT were very similar [5]; however, significant differences in expansion can be observed depending on the non-reactive control fine or coarse aggregates (to be used in combination with reactive coarse or fine aggregates, respectively) used in the test [6,7].

Concrete prism (or accelerated mortar bar) tests are conducted in well-controlled laboratory conditions, conditions that cannot, however, predict whether or not expansion/deterioration will develop under different field conditions and at what rate. Table 7 compares the time to reach a 0.040% expansion level for concrete prisms tested under controlled laboratory conditions and for blocks exposed outdoors, both in Ottawa and Texas. The 0.040% expansion "limit" was selected as it generally corresponds to the level at which cracking can be observed on the test specimens (laboratory and field). The results are still incomplete as the selected expansion level has not been reached in a number of the blocks, especially in the case of concrete blocks stored in Ottawa, Canada. Results in Table 7 are compared in terms of the "failure ratio", i.e. the ratio of the time to reach the proposed limit both in the laboratory and in the field. When comparing field and laboratory specimens of the same alkali contents, the failure ratios obtained for specimens tested in Ottawa ranged from 6 to 15, while those tested in Texas are significantly lower, ranging from 1 to 8 with most values being between 1 and 4. When comparing expansions in boosted concrete prisms and unboosted exposure blocks, which better correspond to the reality of concrete structures, the failure ratios for concretes under cooler and warmer climatic conditions ranged between 10 to 16 and 2 to 6 (with one exception, the Sp aggregate at 14), respectively. This suggests that, on average and although wide variations could be observed from one aggregate to another, if all conditions conducive to ASR are maintained, a structure incorporating a certain reactive aggregate could develop noticeable expansion and cracking in the field about 4 to 5 times faster under "warmer" conditions (i.e. such as those prevailing in Texas) compared to those found in "cooler" parts of the world (i.e. like those where colder winter and prolonged freezing conditions are prevailing).

5 CONCLUSIONS

Moderately to highly-reactive aggregates were used to make concrete specimens of different alkali contents, with and without air-entrainment, that were subjected to comparative field and laboratory investigations. The reactive aggregates investigated were found to respond sometimes quite differently to the various conditions investigated (e.g. alkali contents and air entrainment in field specimens, etc.); however, the results obtained in this investigation suggest that "deleterious" ASR expansion (i.e. inducing an expansion level > 0.040%) could be observed between 4 to 5 times faster under "warmer" climatic conditions compared to "cooler" climatic conditions. Such observations apply to control concretes only; investigations are in progress to determine whether or not such conclusions would apply to concretes incorporating preventive measures against ASR, such as supplementary cementing materials or lithium-based admixtures.

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TABLE 1: Aggregates used in the study

Agg. #	Aggregate type		Reactivity Level ‡	Location	Petrography	14-day exp. (%) AMBT ╬
	Coarse	Fine				
NM	Gravel		HR	New Mexico (USA)	Mixed volcanics	1.114
Minn	Crushed		MR	Minnesota (USA)	Orthoquartzite	0.166
Sp	Crushed		HR	Ontario (Canada)	Fine-grained limestone	0.299
Su	Gravel		MR	Ontario (Canada)	Sandstone, quartzwacke, arkose, greywacke & argillite)	0.278
Wy	Gravel		MR	Wyoming (USA)	Not available	0.300
Vir	Crushed		MR	Virginia (USA)	Granite / gneiss	0.090
Penn	Crushed		HR	Pennsylvania (USA)	Greywacke	0.357
HP†	Crushed		NR	Newfoundland (Canada)	High purity limestone	0.001
ER ¶		Natural	NR	San Antonio, Texas (USA)	Natural dolomite carbonate	
Wt		Natural	HR	Texas (USA)	Chert-bearing sand	0.307
Jb		Natural	HR	Texas (USA)	Chert-bearing sand	0.995
CAN†		Natural	NR	Quebec (Canada)	Derived from granite	0.035
YY ¶		Natural	NR	San Marcos, Texas (USA)	Natural dolomite carbonate	

†: non-reactive aggregates used in combination with reactive materials at CANMET
¶: non-reactive aggregates used in combination with reactive materials at the University of Texas
‡ HR: Highly reactive; MR: moderately reactive; NR: non reactive
╬ Average expansion obtained on several control series performed at CANMET

TABLE 2: Chemical Analysis of the Cements

		Chemical elements, oxides (%)							
	Cement	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI	Na_2Oeq
Cements used at CANMET	C1	20.2	61.7	5.5	2.6	2.2	5.0	1.5	0.90
	C2	20.4	62.4	5.1	2.4	2.6	3.1	2.5	0.90
	C3	19.6	60.8	4.9	2.9	2.5	3.3	2.8	0.91
Cements used at UT	C4	19.8	61.6	5.5	2.0	2.3	4.2	1.4	0.95
	C5	19.3	61.5	5.1	3.1	2.6	4.2	2.4	0.85

† Cement C1 came from a plant located in Ontario (Canada); cements C2 & C3 came from a plant located in Québec (Canada) but were obtained at different times; cements C4 and C5 came from a plant located in Pennsylvania (USA) but were obtained at different times.

TABLE 3: Comparison of concrete mix proportioning as designed in accordance with ASTM C 1293 and CSA A23.2-14A requirements.

Aggregates	Ingredients	ASTM C 1293 kg/m³	CSA A23.2-14A kg/m³
Mix # 1	Cement	420	420
Penn reactive coarse	Water	188	188
aggregate +	Stone (dry)	1122	1062
CAN NR fine aggregate	Sand (dry)	543	667
Mix # 2	Cement	420	420
Jb reactive fine aggregate	Water	181	192
+	Stone (dry)	1168	988
HP NR coarse aggregate	Sand (dry)	486	655

Note: the mix proportions were calculated using the following parameters:

Mix # 1

Penn coarse aggregate (HR)
- Dry-rodded bulk density: 1603 kg m³
- Bulk specific gravity (dry): 2.69
- Absorption (%): 0.63

CAN fine aggregate (NR)
- Bulk specific gravity (dry): 2.68
- Absorption (%): 0.81

Mix # 2

HP coarse aggregate (NR)
- Dry rodded bulk density: 1669 kg m³
- Bulk specific gravity (dry): 2.70
- Absorption (%): 0.16

Jb fine aggregate (HR)
- Bulk specific gravity (dry): 2.60
- Absorption (%): 0.55

Specific gravity of the cement: 3.15; W/C: 0.42; air in the system: 7%

Table 4: Expansion of exposure blocks made at CANMET and tested at CANMET and the University of Texas in Austin (exchange series)

Reactive Aggregate	Blocks tested		Expansion (%) vs Time (yrs)			
	CANMET	UT	1	2	3	Time to reach 0.04%
Jb+ (IC51)	•		0.011	0.225	0.365	1.25
		•	0.109	0.448 (+99%)	0.557 (+53%)	<<1
Sp+ (IC52)	•		0.003	0.018	0.042	3
		•	0.000	0.074 (+311%)	0.137 (+226%)	1.55
Su+ (IC53)	•		0.005	0.006	0.006	--
		•	-0.002	0.012 (+100%)	0.051 (+750%)	2.75

TABLE 5 : Exposure block expansion data. The various concrete mixtures are identified as whether they were made with/without added alkalis (NaOH), or with/without air entrainment. The CAN series correspond to blocks that were made and tested at CANMET; the UT series correspond to blocks that were made and tested at the University of Texas.

Agg.	Specimens	Added alkalis	AEA	Expansion (%) as a function of time (years)								
				1	2	3	4	5	6	7	9	10
NM	**CAN IC1**		•	0.014	0.080	0.207						
	CAN M111		•	0.000	0.104	0.185	0.246	0.304		0.390	0.444	0.465
	CAN IC4	•	•	0.069	0.193	0.265						
	UT 1/15	•		0.143	0.244	0.280	0.290	0.291	0.309			
	UT 84/118	•		0.147	0.242	0.306	0.367					
	UT 98/136	•	•	0.257	0.288	0.319	0.386					
Minn	**CAN IC2**		•	-0.001	-0.003	0.001						
	CAN IC3	•	•	0.000	-0.005	0.002						
	CAN M174	•	•	-0.005		0.002	0.009	0.015	0.025	0.023		
	UT 62/92			0.003	0.011	0.029	0.093					
	UT 60/89	•		0.014	0.133	0.169	0.221					
	UT 89/131	•	•	0.000	0.000	0.014	0.061					
Sp	**CAN M34**		•	0.000	0.013	0.027	0.055	0.074	0.088	0.119	0.149	0.165
	CAN M25	•	•	-0.003	0.022	0.040	0.069	0.088	0.099	0.133	0.183	0.216
	CAN IC13	•	•	0.006	0.009	0.032						
	UT 33/54			0.016	0.096	0.127	0.137	0.155				
	UT 2/7	•		0.045	0.128	0.165	0.207	0.240	0.268			
	UT 76/106	•	•	0.034	0.108	0.196	0.250					
	UT 106/144	•	•	0.055	0.162	0.231						
Su	**CAN M11**		•	-0.004	-0.004	0.005	0.006	0.015	0.030	0.032	0.069	0.120
	CAN M18	•	•	-0.006	-0.006	0.004	0.008	0.019	0.040	0.043	0.075	0.138
	UT 34/52			-0.001	0.012	0.034	0.075	0.141				
	UT 3/8	•		-0.014	0.034	0.088	0.112	0.185	0.243			
	UT 75/105	•	•	-0.001	0.022	0.110	0.203					

TABLE 5 (cont'd) : Exposure block expansion data. The various concrete mixtures are identified as whether they were made with/without added alkalis (NaOH), or with/without air entrainment. The CAN series correspond to blocks that were made and tested at CANMET; the UT series correspond to blocks that were made and tested at UT

Agg.	Specimens	Added alkalis	AEA	Expansion (%) as a function of time (years)								
				1	2	3	4	5	6	7	9	10
	CAN IC28		•	0.007	0.028							
	CAN IC 29	•	•	0.009	0.031							
Wy	**CAN M168**		•	-0.006	0.032	0.075	0.112	0.143	0.158	0.120		
	UT 81/115			0.008	0.105	0.173	0.218					
	UT 82/116	•		0.021	0.128	0.190	0.594					
	UT 83/117	•	•	0.027	0.140	0.205	0.244					
	CAN IC 30		•	0.006	0.015							
	CAN IC 21	•	•	0.006	0.007	0.033						
Wt	**UT 21/36**			-0.010	0.009	0.077	0.532	0.582*	0.693*			
	UT 9/1	•		0.015	0.263	0.487	0.651	0.845	0.805			
	UT 79/113	•	•	0.012	0.177	0.508	0.616					
	UT 114/152	•		0.060	0.387	0.640						
	CAN IC37		•	0.011	0.012							
	CAN IC38	•	•	0.018	0.020							
Vir	**UT 67/96**			-0.003	0.000	-0.002¶	0.015					
	UT 68/97	•		-0.003	0.000	0.006¶	0.032					
	UT 77/111	•	•	-0.005	-0.001†	0.002	0.039					
	CAN IC45		•	0.005	0.009							
	CAN IC46	•	•	0.008	0.011							
Penn	**UT 63/91**			0.000	0.016†	0.042	0.084	0.133				
	UT 61/90	•		0.002	-0.005†	0.025	0.067	0.137				
	UT 78/112	•	•	-0.007	0.058†	0.133	0.181					

* average side measurements only as top expanded beyond comparator measurement
† expansion measurement made at ~ 1.5yr ¶ expansion measurement made at ~ 3.5yr

TABLE 6 : Concrete Prism expansion data (38°C, R.H. . 95%)

Agg	Sample ID	Added alkalis	AEA	Expansion (%) vs time (weeks)						
				1	4	8	13	26	39	52
	CAN IC1		•	0.003	0.017	0.064	0.115	0.210	0.241	0.269
	CAN M111		•	-0.006	0.066	0.141	0.197	0.290		0.393
NM	**CAN IC4**	•	•	0,000	0,034	0,082	0,125	0,232	0,278	0,320
	UT 1/15	•		-	0,039	0,077	0,091	0,129	0,146	0,159
	UT 84/118	•		-0.047	0,040	0,062	0,091	0,133	0,164	0,178
	UT 98/136	•	•	0.008	0,032	0,063	0,085	0,121	0,160	0,184
	CAN IC2		•	-0.001	0,004	0,005	0,009	0,017	0,035	0,054
	CAN IC3	•	•	0.003	0,006	0,014	0,022	0,034	0,079	0,118
Minn	**CAN M174**	•	•	0.003	0,002	0,009	0,006	0,036	0,061	0,094
	UT 62/92			0,001	0,005	0,005	0,016	0,017	0,031	0,050
	UT 60/89	•		0,003	0,004	0,006	0,020	0,036	0,065	0,098
	UT 89/131	•	•	0,001	-	0,010	-	0,032	0,049	0,047
	CAN M34		•	0,003	0,008	0,021	0,049	0,097	0,120	0,137
	CAN M25	•	•	-0,005	0,004	0,014	0,037	0,124	0,161	0,184
	CAN IC13	•	•	0,000	0,006	0,032	0,093	0,190	0,231	0,257
	CAN IC52	•	•	0,008	-0,002	0,020	0,069	0,163	0,190	0,217
Sp	**UT 33/54**			0,001	0,007	0,012	0,022	0,048	0,065	0,115
	UT 2/7	•		0,009	0,022	0,071	0,112	0,163	0,188	0,204
	UT 76/106	•	•	-0,001	0,010	0,056	0,096	0,152	0,188	0,201
	UT 106/144	•	•	-0,005	0,007	0,035	0,069	0,089	0,148	0,168
	CAN M11		•	0,001	0,000	0,003	0,004	0,011	0,020	0,035
	CAN M18	•	•	0,000	-0,004	-0,006	0,003	0,019	0,042	0,075
	CAN IC 53	•	•	0,005	-0,005	-0,001	0,008	0,065	0,128	0,171
Su	**UT 34/52**			-0,006	0,001	0,004	0,006	0,013	0,020	0,033
	UT 3/8	•		0,001	0,006	0,011	0,019	0,070	0,116	0,144
	UT 75/105	•	•	0,004	0,010	0,012	0,015	0,050	0,093	0,126
	CAN IC28		•	0,009	-0,005	0,006	-0,004	0,040	0,103	0,113
	CAN IC 29	•	•	0,004	-0,013	0,002	0,006	0,080	0,146	0,156
Wy	**CAN M168**		•	-0,007	-0,006	0,004	0,015	0,065	0,080	0,090
	UT 81/115			0,000	0,002	0,005	0,009	0,036	0,058	0,075
	UT 82/116	•		0,001	0,011	0,016	0,032	0,077	0,097	0.109 (78w)
	UT 83/117	•	•	-0,002	0,006	0,015	0,030	0,081	0,099	0.116 (78w)

TABLE 6 (cont'd) : Concrete Prism expansion data (38°C, R.H. . 95%)										
Agg	**Sample**	**Added**	**AEA**	**Expansion (%) vs time (weeks)**						
	ID	**alkalis**		**1**	**4**	**8**	**13**	**26**	**39**	**52**
Wt	**CAN IC 30**		•	0,010	0,002	0,008	0,005	0,055	0,139	0,151
	CAN IC 21	•	•	0,000	0,014	0,014	0,042	0,248	0,319	0,400
	UT 21/36			0,001	-0,015	-0,009	-0,007	-0,001	-0,003	0,003
	UT 9/1	•		0,002	0,010	0,015	0,029	0,117	0,185	0,207
	UT 79/113	•	•	0,011	0,015	0,018	0,025	-	0,089	0,121
	UT 114/152	•		-0,003	0,004	0,010	0,019	0,071	0,106	0,130
Vir	**CAN IC37**		•	0,000	-0,004	0,000	-0,001	0,012	0,021	0,024
	CAN IC38	•	•	-0,002	-0,005	-0,001	0,001	0,014	0,029	0,039
	UT 67/96			-0,001	0,003	0,008	0,015	0,022	0,028	0,034
	UT 68/97	•		-0,001	0,002	0,005	0,013	0,027	0,037	-
	UT 77/111	•	•	0,000	0,002	0,005	0,010	0,017	0,037	0,047
Penn	**CAN IC45**		•	-0,002	-0,004	-0,002	0,005	0,039	0,062	0,075
	CAN IC46	•	•	0,000	-0,006	0,004	0,025	0,173	0,236	0,263
	UT 63/91			0,000	0,005	0,008	0,016	0,017	0,027	0,025
	UT 61/90	•		-0,006	0,004	0,010	0,022	0,091	0,139	0,162
	UT 78/112	•	•	-0,002	0,016	0,017	0,033	0,104	0,146	0,167
Jb	**CAN IC51**	•	•	0,005	0,024	0,107	0,191	0,319	0,347	0,359
	UT59			0,003	0,011	0,036	0,105	0,311	0,404	0,440
	UT60	•		0,003	0,039	0,197	0,290	0,463	0,524	0,559

TABLE 7: Comparison of Time to Failure (0.04%) in Outdoor Exposure and Standard Laboratory Testing: Ottawa, Ontario, Canada and Austin, Texas, USA										
Reactive Aggregates	CANMET			University of Texas			Failure Ratio (time to 0.04%, Field/Lab)			
	Sample ID	Time to 0.040% (w)		**Sample**	Time to 0.04% (w)		Comparison of specimens of same alkali levels		Boosted prisms vs unboosted blocks	
		Block	**Prism**	**ID**	**Block**	**Prism**	**CAN**	**UT**	**CAN**	**UT**
NM	**IC1**	72.0	5.2				**14**			
NM	**NM111**	36.0	6.0				**6**		**16**	
NM+				**UT 1 (No Air)**	10,4	4,0		**3**		
NM+	**IC4**	27.0	4.5	**UT 98 (Air)**	16,0	8,0	**6**	**2**		
Minn	**IC2**	> 3y *	43.0	**UT 62 (No Air)**	224,0	52,0		**4**		
Minn+	**IC3**	> 3y *	28.0	**UT 60 (No Air)**	73,0	39,0		**2**		**6**
Minn+	**M174**	> 7y *	28.0	**UT 89 (Air)**	208,0	39,0		**5**		
Sp	**M34**	175.0	11.5	**UT 33 (No Air)**	114,0	26,0	**15**	**4**		
Sp+	**M25**	157.0	14,0	**UT 76**	41,6	8,0	**11**	**5**	**13**	**14**
Sp+	**IC13**	> 3y *	9,0	**UT 106**	62,4	8,0		**8**		
Su	**M11**	370.0	56,0	**UT 34 (No Air)**	161,2	78,0	**7**	**2**		
Su+	**M18**	304.0	38,0	**UT 75**	100,0	25,7	**8**	**4**	**10**	**6**
Wy	**IC28**	> 2y *	26,0	**UT 81 (No Air)**	57,0	39,0		**1**		
Wy+	**IC29**	> 2y *	19,0	**UT 82 (No Air)**	50,0	26,0		**2**		**2**
Wy+	**M168**	115.0	18,0	**UT 83**	41,6	26,0	**6**	**2**		
Wt	**IC30**	> 2y *	24,0	**UT 21 (No Air)**	140,1	>52**		**-**		
Wt+	**IC21**	> 2y *	13,0	**UT 114**	42,0	26,0		**2**		**5.4**
Vir	**IC37**	> 2y *	84,0	**UT 67 (No Air)**	>208.0*	78,0				
Vir+	**IC38**	> 2y *	52,0	**UT 77**	208,0	52,0		**4**		**>4**
Penn	**IC45**	> 2y *	26,0	**UT 63 (No Air)**	156,0	104,0		**2**		
Penn+	**IC46**	> 2y *	15,0	**UT 78**	83,2	26,0		**3**		**6**
**** has not reached the 0.04% expansion at the time of the last measurement***										
*****has not reached the 0.04% expansion at the 1 year measurement***										

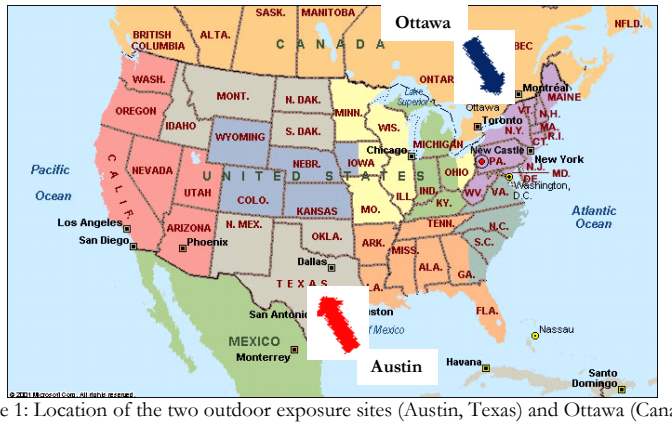
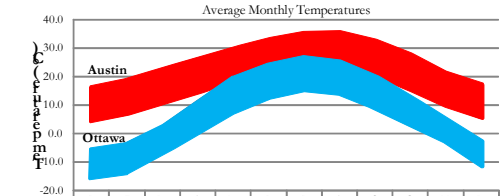


Figure 1: Location of the two outdoor exposure sites (Austin, Texas) and Ottawa (Canada).

A **B**

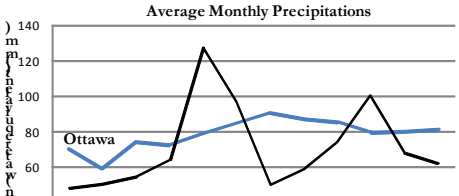
Figure 2: General views of the outdoor exposure site in Texas (A) and in Ottawa (B)

A



	J	F	M	A	M	J	J	A	S	O	N	D
Average	-10.8	-8.7	-2.5	5.7	13.4	18.3	20.9	19.5	14.3	7.8	1.0	-7.1
High	-6.1	-4.1	2.2	10.8	19.1	23.8	26.5	24.9	19.5	12.5	4.8	-3.0
Low	-15.3	-13.3	-7.1	0.6	7.7	12.7	15.4	14.1	9.1	3.0	-2.8	-11.1
Average	10.1	12.5	16.5	20.1	23.9	27.2	29.0	29.1	26.4	21.4	15.4	11.2
High	15.7	18.4	22.5	26.1	29.3	32.7	35.0	35.3	32.3	27.4	21.2	16.8
Low	4.4	6.7	10.5	14.2	18.6	21.7	23.0	22.9	20.4	15.4	9.6	5.5

B



	J	F	M	A	M	J	J	A	S	O	N	D
Ottawa	70,2	58,9	73,9	72,4	79	85	90,6	87,1	85,3	79,4	80,1	81,5
Austin (mm)	48,0	50,5	54,4	63,8	127,	96,8	50,0	58,7	73,9	100,	68,1	62,0

Figure 3: Average yearly temperatures (A) and precipitation (B) at Austin and Ottawa (B)

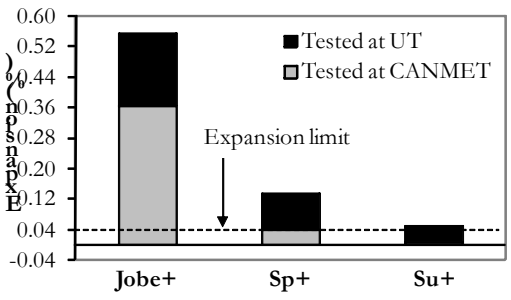


Figure 4: Three-year expansions for exposure blocks made at CANMET but tested in Texas and in Ottawa.

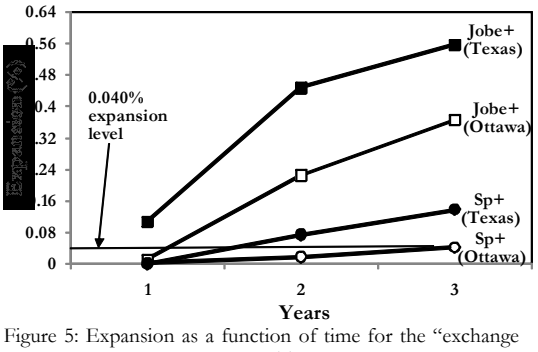


Figure 5: Expansion as a function of time for the "exchange series" exposure blocks tested in Texas or in Ottawa.

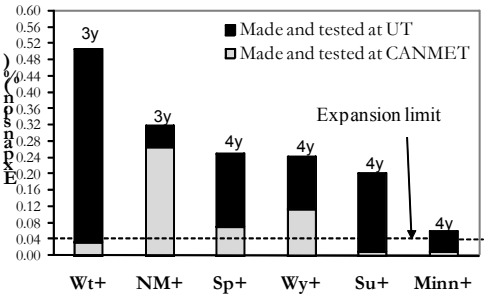


Figure 6: Three or four-year expansions of exposure blocks made and tested in Texas (UT) or in Ottawa (CANMET).

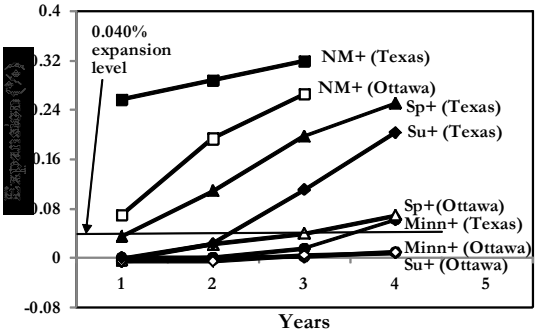


Figure 7: Expansion as a function of time for boosted exposure blocks made and tested in Texas or in Ottawa.

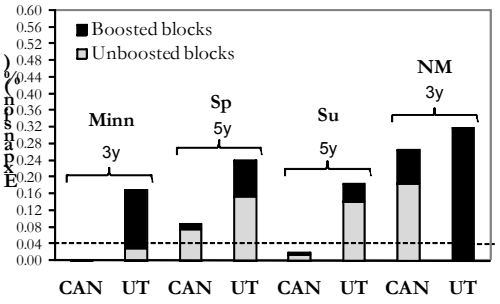


Figure 8: Expansions of boosted vs unboosted exposure blocks tested in Texas (UT) and in Ottawa (CAN).

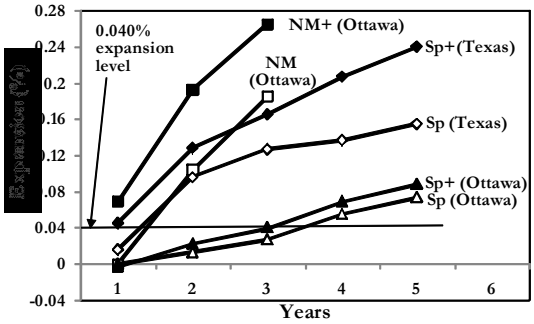


Figure 9: Expansion as a function of time for exposure blocks, boosted or unboosted, made and tested in Texas or in Ottawa.

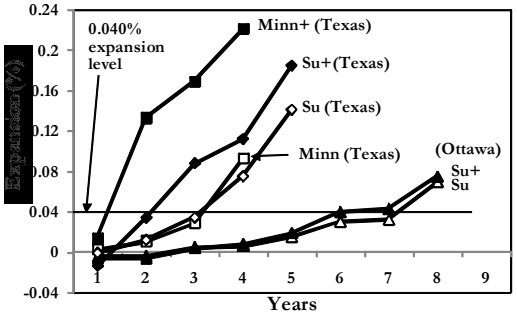


Figure 10: Expansion as a function of time for exposure blocks, boosted or unboosted, made and tested in Texas or in Ottawa.

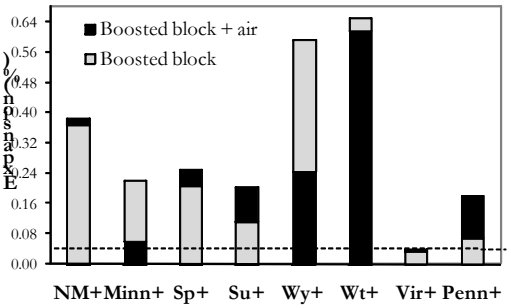


Figure 11: 4-year expansions of boosted exposure blocks, with and without air entrainment, made and tested in Texas (UT).

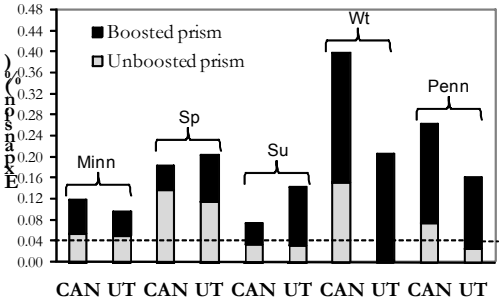


Figure 12: One-year expansion of boosted and unboosted concrete prisms incorporating the various reactive aggregates.