TESTING CONCRETE CORES FOR RESIDUAL EXPANSION DUE TO AAR – AN ATEMPT TO MINIMIZE ALKALI LEACHING AND CONSEQUENT UNREALISTIC EXPANSION DECREASE

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Abstract

Expansion tests were performed at 38°C and >95% RH on concrete specimens incorporating reactive and non-reactive aggregates. The effects on alkali leaching, expansion, and mass variation, of a number of test conditions (e.g. specimen size, specimen surface, air/concrete in test containers) and protective methods against leaching (e.g. silane, sleeve, aluminum foil) were investigated. The specimen surface (i.e. molded cylinders vs cores) did not affect the results. The higher the air/concrete ratio and the smaller the specimen size, the higher the alkali leaching and the lower the expansion and the mass increase. All specimens protected against leaching expanded less than the controls, despite significantly reducing leaching. Wrapping with aluminum foil was the most effective method against leaching but the expansion was still considerably lower than for the controls. Na was always leached in larger proportions than K in the presence of reactive aggregates, with the reverse for the non-reactive aggregate tested, thus suggesting that K ions are more highly integrated in the ASR reaction gel than Na ions.

Keywords : alkali leaching, core testing, protective measures, residual expansion, specimen size

1 INTRODUCTION

The potential for further expansion due to ASR is an important information when planning the schedule for maintenance of affected concrete structures, and for selecting the most appropriate technique(s) for repair. Monitoring the current deformations is the only accurate method of estimating this potential. The current rates of deformation are measured periodically and can be then extrapolated. However, *in-situ* monitoring is usually costly compared to laboratory tests and analyses, and it may take several years to obtain sufficient data to clearly distinguish between permanent and cumulative deformation due to ASR and cyclic movements related to thermal and climatic variations. On the other hand, expansion tests on concrete cores can supply results in a relatively short period of time, while being less expensive than monitoring. This accounts for their common use in assessing the potential for further expansion of ASR-affected concrete.

Testing cores in humid air at 38°C and >95% RH is the recommended and the most common test method used for evaluating the potential for further expansion of ASR-affected concrete [1, 2]. In this method, the concrete is tested with its proper alkali content and the temperature and humidity conditions are the same as in the concrete prism test (CPT) CSA A23.2-14A or ASTM C 1293 performed for determining the potential for ASR of concrete aggregates. However, as previously discussed in a paper presented at the 12th ICAAR [1], concrete prisms made in accordance with the CPT, 75 by 75 by 300 mm in size, suffer significant alkali leaching during the test [3, 4]. Consequently, the expansion in the test tends to level off due to alkali leaching, which does not normally take place in the field. In other words, the maximum expansion

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the ASR-affected concrete may reach in nature is likely underestimated in the test due to progressive alkali leaching from the cores. This is clear from the results obtained at Laval University for concrete cores taken at different expansion levels in concrete blocks, 230 by 230 by 810 mm in size, tested under the same conditions [5] ; whatever the expansion level at which the blocks were cored, the expansion of the cores levelled off after a relatively short period of time while un-cored companion blocks continued to expand at a regular rate (see Figure 4 in [1]). Based on another study performed at Laval University [6], the smaller the specimens tested (prisms of 56 and 75 mm in side, cylinders of 150 and 250 in diameter), the higher was the expansion in the short term, likely due to easier access of humidity inside the concrete; however, the faster was also the flattening off of the expansion curve and the lower the expansion in the long term (see Figure 3 in [1]); this was due to more alkali leaching, as confirmed by measurements of the soluble alkali content of the specimens tested at the end of the tests, using the hot-water extraction method [7].

Considering the relatively low expansion rates obtained for most field concretes tested, (mainly due to lower alkali contents compared with laboratory specimens which are usually alkali-enriched by adding NaOH), and the necessity to often perform the test up to two years, it was then highly recommended [1] to test cores of 150 mm ø to minimize alkali leaching and to prevent the expansion to level off before the expansion results become statistically significant. However, cores of 100 mm in diameter are more practical. In addition to the specimen size, the rate and the extent of alkali leaching during core expansion testing is likely also affected by other parameters such as the water-to-cement ratio. On the other hand, such leaching could be potentially reduced by using an appropriate protective measure.

This study was initiated with the objective of determining, in the presence of reactive and non-reactive aggregates, the effect of various concrete parameters or test conditions on alkali leaching, expansion, and mass variation : water/cement, specimen size (diameter of cylinders), nature of the specimen surface (molded cylinders vs cores), air/concrete volume ratio in the test containers, and, more importantly, various protective methods against alkali leaching. The main objective of this study, conducted through a M.Sc. research program [8], was to reduce alkali leaching when testing cores for expansion in humid air at 38°C and >95% RH to better approach the maximum residual expansion that the concrete under test could reach in nature.

2 MATERIALS AND METHODS

2.1 Materials

Four (4) different coarse aggregates were tested : two highly-reactive siliceous limestones from Québec City (QC) and Ontario (Spratt quarry ; SP), a highly-reactive volcanic gravel from New Mexico (NM), and a non-reactive limestone from Québec (Limeridge quarry ; LR). The fine aggregate used for all concrete mixtures was a non-reactive natural granitic sand from the Québec City area.

Two CSA Type GU or ASTM Type I portland cements were used with Na_2O_{eq} contents of 0.82% (0.26% $Na_2O + 0.85\%$ K₂O) and 1.25% (0.44% $Na_2O + 1.24\%$ K₂O) Na_2O_{eq} .

2.2 Concrete mixtures, test specimens, and curing

Five concrete mixtures were made using 420 kg/m³ of a cement at 0.82% or 1.25% Na₂O_{eq}, a coarse/fine aggregate of 60/40, and a water/cement of 0.40, 0.43 or 0.50 (Table 1). NaOH was added with the lower-alkali cement to obtain 1.25% Na₂O_{eq} by mass of cement, such as all mixtures contained 5.25 kg/m³ Na₂O_{eq}. However, after NaOH addition (+0.43% Na₂O), the Na₂O content increased from 0.26% to 0.69% with the cement at 0.82% Na₂O_{eq}, while remaining at 0.44% with the cement at 1.25% Na₂O_{eq}.

Concrete specimens of different sizes were made : (1), cylinders of 75 mm ø by 150 mm in length, 100 by 200 mm, and 150 by 250 mm, and (2), blocks of 230 by 230 by 810 mm. All specimens were cured for 24 h in their mold. After demolding, 100-mm cores were taken from the blocks and cut to 200 mm in length,

and metallic studs were fixed at both ends of all cores and cylinders to allow axial length measurements. The specimens were then cured in a wet room at 23°C and 100% RH for 7 or 49 days (Table 1).

2.3 Protective measures against leaching and expansion tests

After curing, a number of cylinders of 100 mm \emptyset were subjected to various protective measures against leaching (Table 1 : mixes 1 and 2), then all specimens (either protected or not), were stored upright above water at 38°C and >95% RH in sealed plastic pails of 30L capacity. The inner lateral side of each pail was covered with terry cloth, and the inner side of the cover as well. Before testing, the cloth was presaturated with water and three litres of water were placed in each pail. Only one cylinder of 150 mm \emptyset was stored per pail compared with three cylinders or cores of 75 and 100 mm \emptyset . However, the effect of the air/concrete volume ratio in the containers was investigated by placing only one cylinder of 100 mm \emptyset per pail (mix 2). This ratio also necessarily varied with the specimen diameter (Table 1 : mixes 3, 4, and 5). The protective measures tested against leaching were : (1), no protection at all (controls) ; (2), storage in a small/tight (Sl-) or large/loose (Sl+) plastic sleeve sealed at the top but open at the bottom ; (3), wrapping with three sheets of adhesive aluminum foil on all faces (Al+) or on the lateral face only (Al-) (4), application of a silane-based sealer (Masterseal SL 40) at a dosage of 0.5 (Si-) or 1.1 (Si+) L/m². In the latter case, the specimens were allowed to dry for 14 days at room conditions before being sealed and tested.

2.4 Periodic measurements (mass, expansion, and alkali leaching)

During storage at 38°C and >95% RH, each specimen was periodically measured hot for mass and axial length variations up to 411 days or more. At different times, 10-ml samples of the bottom water were taken from each container and analysed for Na and K. The percentages of Na₂O, K₂O, and Na₂O_{eq} leached from the concrete specimens in each container were then calculated with respect to the total masses of Na₂O and K₂O supplied by the cement and the NaOH addition (when made) to the original concrete specimens, and the known volume of water at the bottom of the container (3 litres at the beginning of the tests). The amount of water at any time was calculated taking in account : (1), the amount of alkalies (Na and K) supplied by the tap water placed in the container ; (2), the periodic removal of water for chemical analysis (10 ml each time) ; (3), the water losses when measuring for mass and length due to the wiping of the specimens with a wet cloth and evaporation (estimated to 20 ml each time by weighing specimens before wiping and after measurements), (4), the progressive absorption of humidity by the test specimens (equal to the mass gain), and (5), the water contribution by gravity from the originally saturated cloth covering the inner surfaces of the container (estimated to 300 ml per container for the all testing period, based on the amount of water extracted after wringing out saturated cloths at the beginning of the test and partially-dried cloths at the end).

2.5 Summary of parameters under study

The (27) different sets of concrete mixtures and experimental conditions tested, each one involving three concrete specimens, allowed the evaluation of the effect of all following parameters on expansion, mass increase, and alkali leaching of the concrete specimens tested (Table 1) : aggregate type and reactivity, water/cement, specimen size, specimen surface (molded cylinders vs cores), air/concrete volume ratio in the test containers, protective measures against leaching, and Na₂O-K₂O differential leaching.

3 RESULTS AND DISCUSSION

Whatever the test conditions, the higher the expansion due to ASR, the higher was generally the mass increase. Due to space limitations, the mass variation results will not be presented hereafter. For their part, the expansion and alkali leaching results are shown in Figures 1 to 6, each one made of two graphs with expansion on the left and alkali leaching on the right. Each point on these graphs corresponds to the average obtained for the set of three specimens of the same mixture subjected to the same test conditions. Considering the number of parameters and test conditions under study, it was found more practical to discuss the results of each parameter or condition investigated immediately after their presentation.

3.1 Influence of aggregate type and reactivity (control 100 mm cylinders of all mixes)

The expansion and leaching results obtained for the control 100 mm cylinders of all mixes are presented in Figure 1 and Table 2. It must be mentioned that these mixes were presenting some differences with respect to the water/cement (0.43 for mix 1, 0.50 for mixes 2, 4, and 5, and 0.40 for mix 3) and the cement used (1.25% Na₂O_{eq} for mixes 1 and 2, and 0.82% Na₂O_{eq} + NaOH up to 1.25% Na₂O_{eq} for mixes 3, 4, and 5). Consequently, due to the potential effect of these two variable parameters, the absolute results obtained for the different aggregates tested cannot be strickly compared with each other.

As expected, the non-reactive LR limestone did not induce significant expansion (0.024% after 434 d), while all three highly-reactive aggregates caused expansion ranging from 0.27% to 0.30% after 411 to 487 d (Figure 1). However, whatever the expansion, the % of Na₂O_{eq} leached was always important : 29% to 39% at the end of the tests for the control 100-mm cylinders of each mix, for an average of 32% (Table 2). The amount of leaching thus seems not related to ASR-related microcracking and expansion, since the LR non reactive concrete was leached at the same extent (33%) as the 4 other highly expansive concretes.

3.2 Influence of the air-to-concrete volume ratio in test containers (QC mix 2: 4.7 vs 16.2)

Figure 2 and Table 2 show that a ratio of 16.2 (1-100 mm cylinder per pail) induced much more alkali leaching than a smaller ratio of 4.7 (3-100 mm cylinders per pail). As a result, the ASR expansion was much lower, even leveling off after only about 150 days. It thus appears that limiting this ratio at a minimum could be beneficial when conducting residual expansion tests on cores, particularly when considering that field concrete usually contains less alkalies than laboratory concrete. Moreover, controlling this ratio in the CPT CSA A23.2-14A or ASTM C 1293 could contribute at reducing the interlaboratory variation in this test.

3.3 Influence of specimen size (NM mix 3, SP mix 4, LR mix 5 : 75 vs 100 vs 150 mm cylinders)

For all three aggregates tested for specimen size, even the non-reactive one, the higher the specimen diameter, the lower the alkali leaching and the higher the expansion (Table 2, Figure 3). These results confirm those from a previous study where, however, the smaller the specimens tested, the higher was the expansion in the short term [1, 6]. It must be mentioned that the air/concrete ratio in the test containers also varied with the specimen size, being 12.6, 4.7, and 5.1, for the 75, 100, and 150 mm cylinders, respectively. Consequently, the differences observed could be related, at least in part, to differences in this ratio. For instance, the highest leaching and lowest expansion for the 75 mm cylinders could be partly due to the highest air/concrete ratio involved. However, the effect of the specimen size is not doubtful since this ratio is quite similar for the two other sizes tested (4.7 and 5.1, for the 100 and 150 mm specimens, respectively). Once again [1], in order to minimize alkali leaching, then to optimize the residual expansion obtained, the use of 150-mm cores, despite being less practical than 100-mm cores, is highly recommended when conducting residual expansion tests on cores, particularly when considering that field concrete usually contains less alkalis than laboratory concrete.

3.4 Influence of the water/cement (QC mix 1 vs QC mix 2: 0.43 vs 0.50)

Table 2 and Figures 4 and 5 present the results obtained for the control (un-protected) and protected 100-mm cylinders of the QC mixes 1 and 2. The water/cement was the only difference between the two mixes (0.43 vs 0.50). For each protective measure tested (including the controls), the alkali leaching and

expansion results of both test series are quite similar. This may suggest that expansion and leaching are not influenced by the water/cement, which could be surprizing, considering the likely related differences in strength and permeability. A literature survey on the effect of the water/cement [6] showed that the conclusions on the subject greatly varied from one study to another. It must be mentioned that, when the cement dosage and the concrete alkali content remain constant (present study), a lower water/cement results in a lesser amount of pore water, which thus presents a higher alkali concentration and a consequent higher pH; the risk for ASR is thus increased. On the other hand, the corresponding concrete is more resistant and less permeable. These both opposite effects may have counterbalanced for each other.

3.5 Influence of specimen surface (QC mix 2; molded cylinders vs cores of 100 mm ø)

Table 2 and Figures 5 and 6 present the results obtained for the control and protected 100 mm specimens of the QC mix 2. The nature of the specimen surface is the only difference between these two figures (i.e. molded cylinders vs drilled cores, respectively). For the controls and each protective measure tested, the results are quite similar for cylinders and cores.

3.6 Influence of protective measures against alkali leaching (QC mix 1, QC mix 2)

The effect of various protective measures against alkali leaching has been investigated in the case of the QC mixes 1 (w/c = 0.43, 100 mm cylinders) and 2 (w/c = 0.50, 100 mm cylinders and cores), for a total of 3 test series. The results appears in Table 2 and Figures 4 to 6. With respect to the control specimens, all protective measures tested significantly decreased the ASR expansion. For each test series, the use of silane resulted in the lowest expansion, which is not surprizing considering the well-known beneficial effect of silane against ASR expansion [9]. However, the use of silane is also associated with the highest values of alkali leaching. This was not expected and cannot be explained for the time being. Also, it must be mentioned that, under the high humidity conditions involved, the mass of the silane-sealed specimens also increased significantly and progressively during the tests, sometimes more than for their respective control; this was observed even after substracting the rapid gain at the beginning of the test due to the 14-d drying period at room conditions to which these specimens were subjected before being sealed and tested. The use of a small/tight or a large/loose sleeve significantly reduced the expansion at about the same extent as the use of silane, but the alkali leaching was only reduced with a small sleeve. By far, the lowest leaching values were obtained with aluminum foil, particularly when applied on all faces of the specimens tested. Unfortunately, the corresponding final expansions were only 60 to 70% with respect to the controls and, based on the trends observed, the Al-protected specimens should not expand more than the controls in the longer term.

The above results show that even three layers of adhesive aluminum foil do not perfectly seal the test specimens; this foil likely became finely porous due to the unstability of aluminum in alkaline solutions. In other words, some humidity and alkali exchanges also took place in the case of the specimens that were totally wrapped with aluminum, despite being relatively limited.

The overall results obtained regarding the protective measures against alkali leaching (and the principal objective of this study as well), are quite disappointing considering that none of the measures tested was capable of reducing alkali leaching <u>and</u> increasing the expansion at the same time, such as the best results (i.e. highest expansions) were obtained for the unprotected control specimens.

3.7 Differential Na₂O/K₂O leaching (all mixes)

Table 2 also presents the % of Na₂O and K₂O leached at the end of the tests. For instance, in the case of the QC mix 1 control, the % of Na₂O and K₂O leached were 34% and 26% of the original Na₂O and K₂O concrete contents, respectively, thus leading to a [% of Na₂O leached]/[% of K₂O leached] of 1.29.

For the QC mixes 1 and 2, made with the cement at 1.25% Na_2O_{eq} (0.44% $Na_2O + 1.24\% K_2O$), whatever the specimen surface (i.e. cylinders vs cores) or the protective measure involved (including the controls), Na₂O was always leached in greater proportion than K₂O, by 22% on average for the 18 experiments involved. Considering that the hydrated radius of Na ions is greater than that of the K ions, this cannot be explained by a higher ion mobility. However, it could be that K ions are slightly more integrated in the ASR reaction gel than Na ions. This assumption is supported by the fact that the non-reactive LR concrete presents the smallest [% of total Na2O leached]/[% of total K2O leached] ratios, in fact the only ones under unity (e.g. 0.95 for the 100-mm cylinders). The above assumption is also supported by the fact that, for two (NM, LR) of the three mixes involved (NM, SP, LR), the 75-mm cylinders, which expanded significantly less than the 100- and 150-mm cylinders (due to more alkali leaching, as discussed before) and which thus likely contain less alkali-silica reaction gel, present %Na2O/%K2O leaching ratios significantly lower than the larger cylinders (NM mix : 1.32 for 75-mm cylinders vs 1.60 and 1.54 for 100- and 150-mm cylinders; LR mix: 0.78 vs 0.95 and 0.94; Table 2). The relatively low ratios for the SP mix (1.03 for 100mm cylinders) with respect to the three other reactive mixes (1.29, 1.30, and 1.58 for the control 100-mm cylinders of the QC mix 1, QC mix 2, and NM mix; Table 2), could be related to some K leached out from the potassic clay minerals (illite, smectite) present in the aggregate. This is possible considering that the extent of leaching for the SP mix (39% for 100-mm cylinders ; Table 2) was significantly higher than for the three other mixes (29%, 30%, and 31% for the control 100-mm cylinders; Figure 1 and Table 2).

4 CONCLUSIONS

Testing concrete cores in humid air at 38°C and >95% RH is commonly used to evaluate the residual expansion of ASR-affected concrete. However, the maximum expansion this concrete may reach in nature is likely underestimated due to progressive alkali leaching from the cores during the tests. In the presence of selected reactive (3) and non-reactive (1) aggregates, the effect of a number of parameters on expansion, mass variation, and alkali leaching have been investigated in this study as a function of time : water/cement (0.43 vs 0.50), specimen surface (molded cylinders vs drilled cores), specimen size (75, 100, and 150 mm \emptyset), air/concrete volume ratio in the test containers (one or three test specimens per pail), differential leaching between Na₂O and K₂O, and various protective measures against alkali leaching (tight and loose plastic sleeves open at the base, silane-based sealer at two different dosages, adhesive aluminum foils covering all faces or just the lateral surface of the cylindrical specimens). This study involved a total of 5 concrete mixtures and 27 different sets of test conditions. The following conclusions can be drawn :

- For all test conditions, the higher the ASR expansion, the higher was generally the mass increase.
- Whatever the ASR expansion level, the % of Na₂O_{eq} leached was always important (29 to 39%) and quite similar for the control specimens of each mix, even in the presence of the non-reactive aggregate. The extent of alkali leaching thus seems not influenced by ASR-related microcracking and expansion.
- The results were also similar for the two mixes made with the same reactive aggregate but with different water-to-cement ratios (0.43 vs 0.50). Both mixes were containing the same alkali content such as two opposite effects related to a lower ratio may have counterbalanced for each other : (1), lower amount of residual pore water, which thus contains more alkali and OH ions (higher pH) and (2), higher strength and lower permeability. However, the extent of alkali leaching was similar for both mixes.
- For the three mixes/aggregates involved, the smaller the specimen size, the higher the alkali leaching and the lower the expansion and the mass increase. In order to minimize alkali leaching, then to optimize the residual expansion obtained, the use of 150-mm cores, despite being less practical than 100-mm cores, is highly recommended when conducting residual expansion tests on cores, particularly when considering that field concrete usually contains less alkalis than laboratory concrete.

- Na₂O was always leached in larger proportions than K₂O in the presence of reactive aggregates, with the
 reverse for the non-reactive aggregate tested. This may suggest that K ions are more highly integrated in
 the ASR reaction gel than Na ions. This assumption is also supported by the fact that the less-expansive
 75-mm cylinders tested generally present Na₂O/K₂O leaching ratios lower than the more expansive 100and 150-mm cylinders.
- The nature of the specimen surface (i.e. molded vs cored) did not significantly affect the leaching results.
- * The lower the air/concrete volume ratio in the test containers, the lower the alkali leaching and the higher the expansion and the mass increase. It thus appears that using a low ratio could be beneficial when conducting residual expansion tests on cores, particularly when considering that field concrete usually contains less alkalis than laboratory concrete. Moreover, controlling this ratio in the CPT (CSA A23.2-14A or ASTM C 1293) could contribute to reduce the interlaboratory variation in this test.
- All specimens protected against leaching expanded less than the controls, despite significantly reducing leaching. Wrapping with aluminum foil was the most effective method against leaching but the expansion was still considerably lower than that of the controls. The overall results obtained regarding the protective measures against leaching (and the principal objective of this study as well), are quite disappointing considering that none of the measures tested was capable of reducing alkali leaching <u>and</u> increasing the expansion at the same time, such as the best results obtained (i.e. highest expansions) were obtained for the un-protected control specimens.

5 **REFERENCES**

- [1] Bérubé, M.A., <u>Smaoui</u>, N., and <u>Côté</u>, T. (2004) : Expansion tests on cores from ASR-affected structures. 12th Int. Conf. on AAR, Beijing, China : 821-832.
- [2] Bérubé, M.A., Frenette, J., Pedneault, A., and Rivest, M. (2002): Laboratory assessment of the potential rate of ASR expansion of field concrete. Cement, Concrete, and Aggregates, **24** (1) : 13-19.
- [3] Rogers, C.A., and Hooton, R.D. (1993) : Reduction in mortar and concrete expansion with reactive aggregates due to alkali leaching. Cement, Concrete, and Aggregates, **13** : 42-49.
- [4] Rivard, P., Bérubé, M.A., Ollivier, J.P., and Ballivy, G. (2003) : Alkali mass balance during the accelerated concrete prism test for alkali-aggregate reactivity. Cement and Concrete Research, 33 (8) : 1147-1153.
- [5] Smaoui, N. (2003) : Contribution à l'évaluation du comportement structural des ouvrages d'art affectés de réaction alkalis-silice. Ph.D. Thesis, Laval University, Québec City, Canada, 353 p. + annexes.
- [6] Landry, M. (1994) : Influence de l'air occlus, du rapport eau/ciment, de la granulométrie des granulats et de la dimension des éprouvettes testées sur la réaction alcalis-granulats dans le béton. M.Sc. Memoir, Laval University, Québec City, Canada, 105 p.
- [7] Bérubé, M.A., Frenette, J., Rivest, M., and Vézina, D. (2002) : Measurement of the alkali content of concrete using hot water extraction. Cement, Concrete, and Aggregates, 24 (1) : 28-36.
- [8] Côté, T. (2009) : Gestion des ouvrages en béton affectés de réactivité alcalis-silice : contribution à la détermination de l'expansion atteinte à ce jour et de l'expansion résiduelle à venir. M.Sc. Memoir, Laval University, Québec City, Canada : 117p. + annexes.
- [9] Bérubé, M.A., Chouinard, D., Frenette, J., Boisvert, L., Pigeon, M., and Rivest, M. (2002) : Effectiveness of sealers in counteracting ASR in plain and air-entrained laboratory concretes exposed to wetting and drying, freezing and thawing, and salt water. Can. J. Civ. Engng., 29 : 289-300.

TABLE 1 : Characteristics of concrete mixtures, test specimens, and testing conditions ^a .									
Parameter	Mix 1	Mix 2 Mix 3 Mix 4		Mix 5					
Coarse aggregate	QC limestone	QC limestone	NM gravel	SP limestone	LR limestone				
Water/cement	0.43	0.50	0.40	0.50	0.50				
Cement (%Na2O _{eq})	1.25	1.25	0.82 + NaOH up to 1.25	0.82 + NaOH up to 1.25	0.82 + NaOH up to 1.25				
Specimen ø (mm)	100	100	75, 100, 150	75, 100, 150	75, 100, 150				
Specimen type	Cylinders	Cyl. & cores	Cylinders	Cylinders	Cylinders				
Air/concrete volume ratio (30L-pails)	4.7 (3-100 mm)	4.7 (3-100 mm) 16.2 (1-100 mm)	12.6 (3-75 mm) 4.7 (3-100 mm) 5.1 (1-150 mm)	12.6 (3-75 mm) 4.7 (3-100 mm) 5.1 (1-150 mm)	12.6 (3-75 mm) 4.7 (3-100 mm) 5.1 (1-150 mm)				
Protective measures ^b	None, Sl-, Sl+, Al+, Si+	None, Sl-, Sl+, Al-, Al+, Si-, Si+	None	None	None				
Number of tests	5	13	3	3	3				
 ^a For each parameter (row), colored cells correspond to mixes that allow evaluation of the effect of this parameter, within a given mix (yellow cells) or by comparison between different mixes (green cells). ^b None : unprotected control; Sl- or Sl+ : small (tight) or large (loose) plastic sleeve; Al+ or Al- : 3 sheets of Al foil on all faces or on the lateral face only; Si- or Si+ : silane sealer at a dosage of 0.5 or 1.1 L/m². 									

TABLE 2: Expansion, mass increase, and alkali leaching at the end of each test (for 100 mm specimens) ^a .									
Aggregate T and mix (d	Time	Test condition ^b	Expansion (%)		% of total Na ₂ O _{eq} leached		% of total Na ₂ O leached/ % of total K ₂ O leached		
	(days)		cyl.	cores	cyl.	cores	cylinders	cores	
QC mix 1 (w/c = 0.43, 100 mm cyl., cem. 1.25%,		Control	0.29	-	29	-	34/26 = 1.29	-	
	487	Sl- (sleeve)	0.16	-	22	-	28/20 = 1.40	-	
		Sl+ (sleeve)	0.16	-	33	-	37/31 = 1.21	-	
		Al+ (Al foil)	0.18	-	3.2	-	3.4/3.1 = 1.12	-	
± protections		Si+ (silane)	0.15	-	34	-	39/32 = 1.22	-	
		Control (1 cyl.)	0.12	-	54	-	63/51 = 1.24	-	
OC mix 2		Control	0.29	0.30	30	34	36/27 = 1.33	40/32 = 1.26	
$\sqrt{\mathbf{U}} = 0.50$		Sl- (sleeve)	0.16	0.17	21	21	24/20 = 1.24	25/19 = 1.30	
100 mm cyl.		Sl+ (sleeve)	0.15	0.16	29	34	33/27 = 1.24	38/32 = 1.21	
and cores,	411	Al- (Al foil)	-	0.17	-	13	-	14/13 = 1.07	
cem. 1.25%,		Al+ (Al foil)	0.21	0.21	9	6	9.5/9.3 = 1.02	6.4/5.8 = 1.11	
± protections		Si- (silane)	-	0.144	-	39	-	43/38 = 1.11	
		Si+ (silane)	0.13	0.139	37	44	43/35 = 1.21	50/41 = 1.21	
NM mix 3	460	75 mm cyl.	0.27	-	41	-	46/35 = 1.32	-	
(w/c = 0.40,		100 mm cyl.	0.30	-	31	-	38/24 = 1.60	-	
cem. 0.82%+)		150 mm cyl.	0.37	-	18	-	21/14 = 1.54	-	
SP mix 4		75 mm cyl.	0.13	-	68	-	61/55 = 1.12	-	
(w/c = 0.50,	460	100 mm cyl.	0.27	-	39	-	40/38 = 1.03	-	
cem. 0.82%+)		150 mm cyl.	0.41	-	38	-	39/38 = 1.03	-	
LR mix 5	434	75 mm cyl.	0.004	-	40	-	35/45 = 0.78	-	
(w/c = 0.50, cem. 0.82%+)		100 mm cyl.	0.024	-	33	-	32/33 = 0.95	-	
		150 mm cyl.	0.027	-	25	-	24/26 = 0.94	-	
^a For each mix, yellow and green cells correspond to the highest and lowest results, respectively.									

^b Variable air/concrete volume ratio (see Table 1) ; one 150-mm cylinder per pail ; three 75- or 100-mm cylinders or cores per container except in one case (QC mix 2 : orange row : one 100-mm cylinder/pail).



FIGURE 1 : Effect of aggregate type and reactivity (w/c = 0.43 for QC mix1, 0.50 for QC mix2, SP, and LR, and 0.40 for NM) ; cement : 1.25% Na₂O_{eq} for QC mixes 1 and 2, 0.82% Na₂O_{eq} + NaOH up to 1.25% Na₂O_{eq} for NM, SP, and LR ; 100 mm cylinders ; air/concrete = 4.7 ; no protection).



FIGURE 2 : Effect of air-to-concrete volume ratio in test containers (QC mix2 ; w/c = 0.50 ; cement : 1.25% Na₂O_{eq} ; 100 mm cylinders ; air/concrete = 4.7 (3 cylinders/pail) or 16.2 (1 cylinder/pail) ; no protection).



FIGURE 3 : Effect of specimen size (NM mix 3, SP mix 4, LR mix 5; w/c = 0.50 except for NM (0.40); cement : 1.25% Na₂O_{eq}; 100 mm cylinders; air/concrete = 12.6 (75 mm), 4.7 (100 mm) or 5.1 (150 mm); no protection).



FIGURE 4 : Effect of protective measures (<u>QC mix 1</u>; 100 mm <u>cylinders</u>; w/c = 0.43; cement : 1.25% Na_2O_{eq} ; air/concrete = 4.7).



FIGURE 5 : Effect of protective measures (QC mix 2 ; 100 mm cylinders ; w/c = 0.50 ; cement : 1.25% Na_2O_{eq} ; air/concrete = 4.7).



FIGURE 6 : Effect of protective measures (<u>QC mix 2</u>; 100 mm <u>cores</u>; w/c = 0.50; cement : 1.25% Na₂O_{eq}; air/concrete = 4.7).