INFLUENCE OF WETTING-DRYING AND FREEZING-THAWING CYCLES, AND EFFECTIVENESS OF SEALERS ON ASR

M.A. Bérubé[1], D. Chouinard[1], L. Boisvert [2], J. Frenette[1] and M. Pigeon[2]
[1]Department of Geology and Geological Engineering
[2]Department of Civil Engineering
Laval University, Quebec City, Quebec, Canada, G1K 7P4

ABSTRACT

Low and high-alkali concrete cylinders were made with a very reactive siliceous limestone, using air entrainer. After curing, a number of the cylinders were sealed with silane, oligosiloxane, polysiloxane, epoxy resin or linseed-oil. All samples were submitted to various 14-day cycles including periods of humid air curing, drying, wetting in pure or salt water, freezing and thawing. Drying significantly reduced ASR expansion but promoted map-cracking. Freezing greatly increased ASR expansion and map-cracking as well. At the same time, low-alkali samples did not expand nor develop map-cracking. Whatever the exposure conditions, the silane and siloxanes tested reduced ASR expansion to an acceptable level, and the corresponding samples did not show map-cracking. The epoxy resin was not effective. The linseed oil prevented map-cracking while reducing expansion, however not sufficiently. A number of cylinders that were severely deteriorated due to ASR were sealed with silane after 1.5 years. They started to lose mass and contract immediately after being sealed. The silane and siloxanes were also applied on highway dividers showing various degrees of ASR deterioration. Observations over a 4-year period indicate that their aesthetic appearance, particularly with silane, was greatly improved, while internal humidity was reduced.
Keywords: Concrete, Alkali-aggregate reaction, Wetting-drying cycles, Freezing-thawing cycles, Sealers.

INTRODUCTION

The alkali-silica reaction (ASR) can produce various types of defects which result from internal microcracking and expansion of affected concrete members, such as differential movements, deformations, concrete spalling, extrusion of sealers along joints, and surface cracking patterns. However, the development of some defects can be greatly affected by the exposure conditions such as wetting/drying and freezing/thawing.

Wetting/drying cycles are thought to play an important role in the development of the surface cracking patterns, such that the amplitude of this defect may not correlate with internal deterioration (e.g. microcracking and expansion) (Nishibayashi *et al.* 1989). In fact, wetting/drying leads to conditions which are relatively less conducive to reactions (less moisture in dry weather, leaching of alkalies by rain), in the first few centimetres of concrete than in the middle of the concrete mass. The surface concrete thus cracks from tension under the expansive thrust of the underlying concrete. This explains why: (1), cracks observed on the surface of ASR affected concrete members rarely penetrate more than a few centimeters inside concrete; (2), immersed or underground parts of ASR affected concrete members are usually less deteriorated on their surface (higher humidity), even though signs of ASR are observed in the entire concrete mass, and (3), concrete surfaces exposed to the south (more sun and more drying) usually present more map-cracking than sections exposed to the north (Ludwig 1989).

Freezing-thawing cycles accelerates the deterioration once cracking has been started by ASR. Conversely, as experienced by the authors in the case of a landing runway of the Quebec City airport, ASR or related deterioration can be accelerated once the concrete has been cracked by freezing, because humidity can more easily penetrate into the concrete, and because the concrete is weaker and less able to withstand the expansive forces generated by ASR.

However, the application of a good sealer on the concrete surface may reduce the influence of all exposure conditions, thus surface deterioration. Evenmore, as suggested in many papers presented at the last two International Conferences on AAR, held in Japan and in the U.K. in 1989 and 1992, respectively, the application of a good sealer on the surface of relatively thin concrete components exposed to air may reduce ASR and consequent expansion. In most studies, the most interesting sealers corresponded to silane- and siloxane-based types.

The principal objective of this study was to obtain more information about: (1), the effect of freezing/thawing and wetting/drying on expansion and surface deterioration of ASR affected concrete; (2), the mechanisms by which good sealers can reduce ASR expansion and/or surface cracking, and (3), their effectiveness and durability under severe exposure conditions such as those prevailing in North America.

MATERIALS AND METHODS

Laboratory experiments

Concrete specimens. Low-alkali (1.9 kg/m^3 Na_2O_{eq}; 40 cylinders) and high-alkali (4.4 kg/m^3 Na_2O_{eq}; 8 cylinders) concretes were made with a very reactive siliceous limestone, a non-reactive granitic sand, a coarse aggregate/sand ratio of 60/40, 350 kg/m^3 of cement (ASTM type I), a water/cement ratio of 0.5, and using an air entrainer. The concrete samples were molded in plastic pails to give cylinders with a slightly conical shape, an average diameter of ≈255 mm ø (at midlength), a length of ≈310 mm and a mass of ≈38 kg. A low alkali cement containing 0.54% Na_2O_{eq} was used for the low-alkali concrete, while the cement used for the high-alkali concrete contained 0.73% Na_2O_{eq} but was increased to 1.25% by adding NaOH to the mixture water.

Initial curing and early sealing. All cylinders were first cured for 7 days in air at 100% RH and 23°C, in a fog room. In order to evaluate the effect of curing, a few high-alkali specimens were stored in air at 100% RH and 38°C (over water in sealed plastic pails) for the following 21 days, while all other cylinders were exposed in the laboratory at about 35% RH and 23°C. Afterwards, a number of them were sealed with silane (S1), oligosiloxane (S2), polysiloxane (S3), epoxy resin (S4) or linseed-oil (S5) to evaluate the effectiveness of sealers as a preventive measure on new concrete susceptible to ASR. The sealers were all applied in two steps, using a dosage of 0.33 liter/m^2. In the following, the specimens unsealed at 28 days (controls) are first identified by S0.

Test conditions and late sealing. All samples were exposed to various 14-day cycles (C1 to C5) including periods of humid curing (over water in sealed plastic pails), drying, wetting by immersion in tap water or 3% NaCl solution, freezing and thawing (Table 1). At 1.5 years, some samples exposed to cycles C3, C4 and C5, and not sealed at 28 days (first identified by S0), were sealed with the silane S1 and the siloxanes S2 and S3, to evaluate the effectiveness of sealers as a corrective measure for concretes severely affected by ASR. These samples are identified by S0/S1, S0/S2 or S0/S3.

Table 1 Description of the 14-day exposure cycles applied to the concrete cylinders.

Cycle no.	Humid air curing at 38°C & 100% RH[1]	Drying at 38°C & 30% RH	Wetting at 38°C through complete immersion in: tap water	Wetting at 38°C through complete immersion in: salt water[2]	Freezing/thawing in air (24-hour cycles from +25 to -18°C)[3]
C1	14 d	-	-	-	-
C2	14 d	-	30 min	-	-
C3	10 d	4 d	30 min	-	-
C4	7 d	4 d	30 min	-	3 d
C5	7 d	4 d	-	30 min	3 d

[1]: Over water in sealed plastic pails. [2]: 3% NaCl solution. [3]: 16-hour freezing/8-hour thawing.

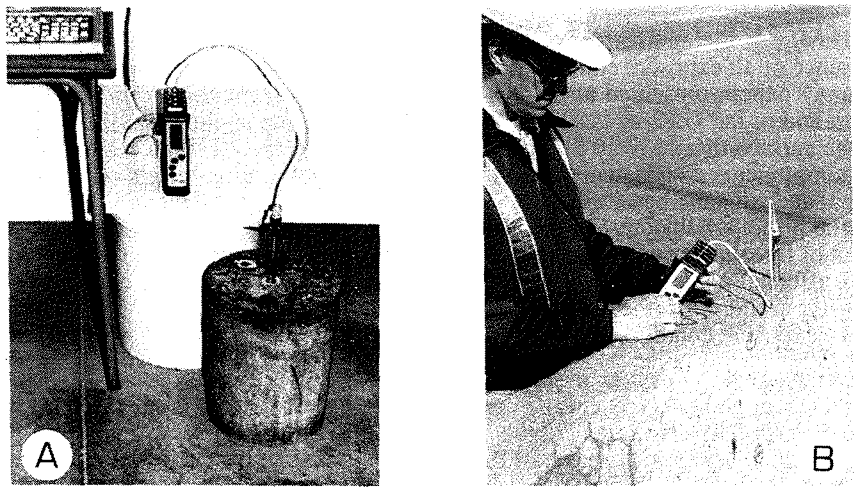

Fig. 1 Humidity measurements in concrete cylinders (A) and highway dividers (B).

Periodical measurements. The mass (immediately after the humid curing, drying and wetting periods, when applied), and the length (immediately after the humid curing period) of samples were measured periodically up to 2.5 years. The samples were also examined periodically for surface cracking. After 1 year, the internal relative humidity was also measured in two high-alkali specimens submitted to cycle C3, unsealed and silane-sealed, respectively, immediately after a period of humid curing. For each specimen, the measurements were performed along two small 20 mm ø boreholes drilled parallel to the axis of the cylinders at about 2 cm and 13 cm (center) from the lateral surface, using a commercial probe (Novasima MS1-E by Defensor) (Fig. 1A).

Field experiments

In August 1991, silane S1 and siloxanes S2 and S3 were also applied on sections of highway dividers showing various degrees of ASR deterioration in Montmorency (severe deterioration), Beauport (moderate deterioration), and Sainte-Foy (fair deterioration). One section in Montmorency was also sealed with another silane, identified S6. These components were inspected periodically since then. During the summer of 1994, gauge reference studs were installed in Montmorency and in Sainte-Foy in silane-sealed (S1) and unsealed sections for periodical expansion measurements. Since then, temperature and relative humidity were also recorded in the same sections along small boreholes, using the same procedure as used for the laboratory samples (Fig. 1B).

RESULTS AND DISCUSSION

Influence of initial curing and exposure conditions

After the first 14-day cycle which allowed the samples previously stored for 21 days at room temperature in the laboratory to absorb most of the water lost, the mass and length variations of these samples were not significantly different from those of the specimens initially cured for 28 days under humid conditions, for each exposure cycle C1 to C5.

All high-alkali samples exposed to cycles C1 to C5 showed high expansion from 0.15% to 0.35% after 2 years (Fig. 2A). Cycle C2 (30-min immersion in water for every period of 2 weeks) did not induce significant differences in expansion and mass (Fig. 2B), compared to samples always stored at 100% RH (C1). A 4-day drying period for every period of two weeks reduced the ASR expansion by about 40%, and the mass of specimens by about 400 g (≈1%) over a period of 2 years (C3 vs C2), but promoted surface deterioration (map-cracking). In fact, the samples exposed to cycle C3 are under humid conditions during 71% of time (10 days per 14-day cycle), compared to 100% for samples exposed to C2. This reduced ASR expansion, as expected. The addition of freezing-thawing to wetting-drying also increased expansion by about 50% (C4 vs C3), despite the fact that corresponding samples were stored for a shorter period of time at 100% RH (7 days per cycle for C4 vs 10 days for C3). Their mass is also greater than that of specimens exposed only to drying (C3). In fact, these samples expanded more and are more microcraked, then they entrapped more water. Freezing-thawing also greatly promoted map-cracking (Fig. 3A). Immersion in salt water rather than tap water before the freezing-thawing cycles increased expansion and enhanced map-cracking as well (C5 vs C4). At the same time, low-alkali samples did not expand nor develop surface cracking, regardless of the exposure cycle.

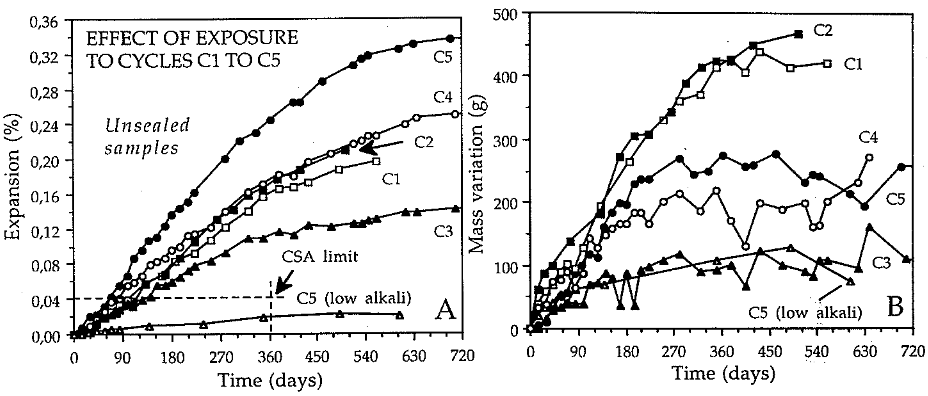

Fig. 2 Expansion (A) and mass variation (B) of unsealed concrete cylinders submitted to exposure cycles C1 to C5.

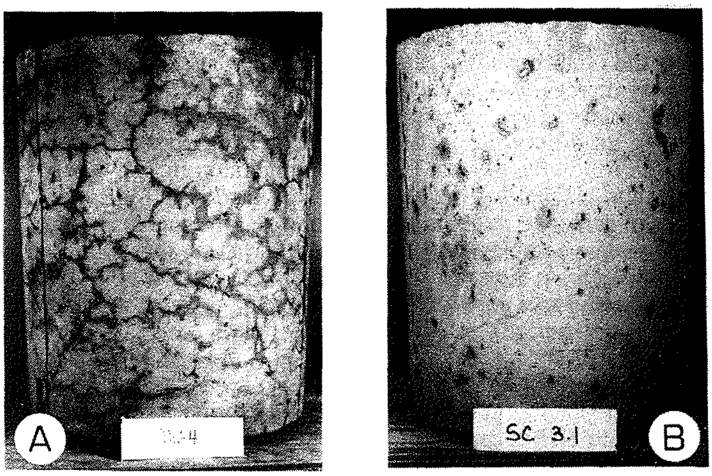

Fig. 3 Unsealed (A) and silane-sealed (B) concrete cylinders exposed to cycle C4, after 1.5 years.

The above results indicate that, in the absence of ASR, wetting-drying and freezing-thawing should not cause damage to air-entrained concretes. However, they contribute greatly to concrete deterioration in the presence of ASR, despite a good air void system. As measured on samples from each concrete batch, the air spacing factor (L bar) varied between 222 and 398 μm, averaging 310 and 290 μm for the high- and the low-alkali concretes, respectively. The above results also confirm that the exposure conditions greatly affect the surface cracking of ASR affected concrete. Indeed, wetting/drying and freezing/thawing promoted map-cracking despite the fact that expansion due to ASR is reduced when the samples are allowed to dry (lower humidity) or to freeze (lower temperature).

Effectiveness of sealers on new concrete susceptible to ASR

The Canadian Standard Association suggests a 1-year limit of 0.04% expansion for concrete exposed to conditions identical to cycle C1. The silane and the two siloxanes tested satisfied this limit for cycles C1 to C4, e.g. even for samples exposed to freezing-thawing, and the corresponding samples did not show map-cracking (Fig. 3B). The expansion only marginally exceeded the above limit for the samples sealed with polysiloxane S3 and exposed to the most severe cycle C5 (e.g. with wetting in salt water before the freezing/thawing cycles) (Fig. 4A). The silane S1 is slightly more effective than the oligosilixane S2, which is slightly better than the polysiloxane S3 (Fig. 4A). The epoxy sealer S4 is not effective in reducing expansion and map-cracking, and greatly changes the appearance of concrete (dark color and waxy luster). The linseed oil prevented map-cracking while reducing expansion by about 60%, however not sufficiently. It also gives a bad appearance to concrete (non uniform color and luster). It is interesting to note that the low-alkali concrete sealed with the silane presented shrinkage since the beginning of the tests.

For each exposure cycle, a good correlation is observed between concrete expansion and mass variation (e.g. humidity absorption or evaporation) (Fig. 4A vs 4B), (except maybe for the epoxy resin), which is not surprizing considering that expansion is directly related to microcracking, which in turn allows water and humidity intake. The mass of the concrete cylinders sealed with silane or siloxane has progressively decreased by more than 400 g (or 1%) over a period of 2 years, whatever the exposure cycle, compared with an equivalent mass increase for unsealed samples (Fig. 4B). The sealed specimens are still loosing mass after 2 years. At the same time, the samples sealed with linseed oil presented lower mass losses, but their mass started to slightly increase after 1.5 years. On the other hand, the mass of the specimens treated with the epoxy resin has progressively increased since the beginning of the tests.

The humidity loss of sealed samples during the 4-day drying period is about two times lower than for the corresponding unsealed samples, but they absorbed much less water during the following 30-min period of immersion in tap or salt water (see Fig. 4C). In the case of all samples not sealed after 28 days (S0, S0/S1, S0/S2 and S0/S3), the mass loss and gain tend to diminish with time, despite increasing expansions, which is likely due to a more complete hydration and/or surface carbonation of concrete (lower surface permeability). At the same time, all samples sealed after 28 days with silane or siloxane showed relatively constant mass loss during drying, and gain during wetting throughout the testing period (see Fig. 4C).

Humidity measurements inside the two 1-year old samples exposed to cycle C4 indicated that the apparent relative humidity is significantly lower in the unsealed and expansive sample (95% RH in center and 96% near surface) than in the sealed and non expansive one (86% RH in center and 81% near surface), particularly in the surface concrete. This suggests in turn that <u>internal humidity</u> conditions over 80 to 85% are necessary for ASR expansion. On the other hand, another study indicated that <u>external humidity</u> as low as 65% RH is sufficient to obtain expansion over 0.04% per year for the same type of concrete, and that the more reactive the aggregate, the lower the critical external humidity level required for significant expansion (Bérubé *et al.* 1994). It is clear that there is a world of difference between internal and external humidity.

The results obtained suggest that a good sealer can reduce ASR expansion to an acceptable level in new concretes and, for sure, consequent surface deterioration (map-cracking), at least for concrete components of less than 255 mm in thickness, which corresponds to the diameter of the cylinders tested in this study. The thickness of many concrete components in service is similar or lower to this value.

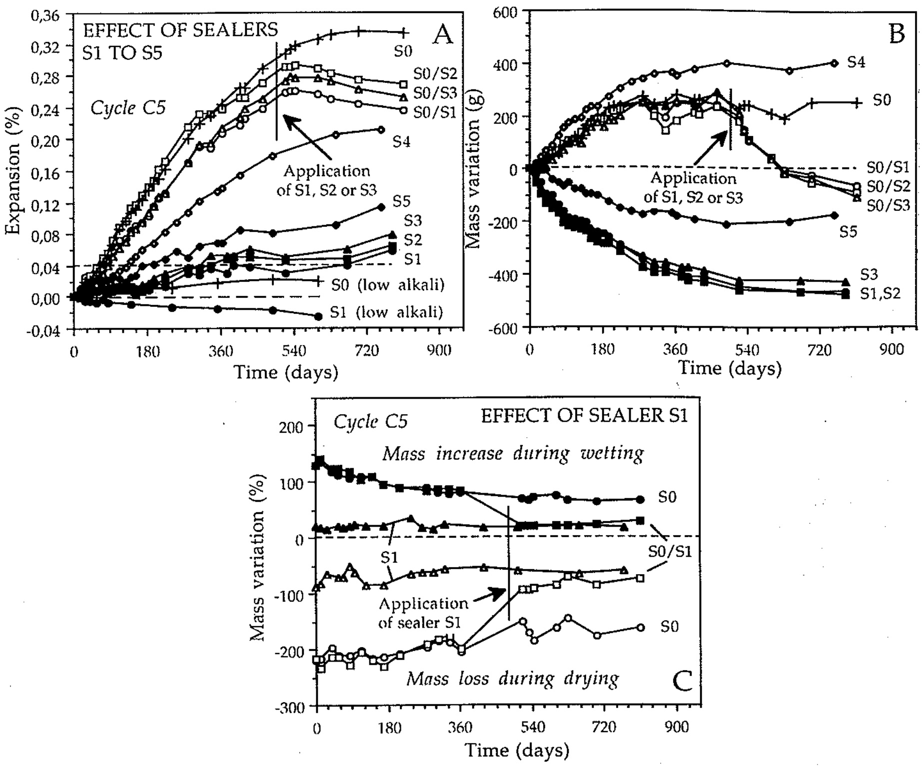

Fig. 4 Expansion (A), cumulative mass variation (B) and mass variation during drying and wetting (C), for sealed and unsealed concrete cylinders exposed to cycle C5.

Effectiveness of sealers on concrete severely affected by ASR

The severely deteriorated samples that were sealed with silane or siloxane after 1.5 years started to lose mass and contract immediately after being sealed (Fig. 4A, samples S0/S1, S0/S2 and S0/S3), even in the presence of wetting-drying and freezing-thawing. Evenmore, during the following six months, they almost lost the total amount of water that they had gained previously (Fig. 4B). Also, the mass loss during drying, and the mass increase during wetting of these samples, which are already highly microcracked, quite rapidly reached values that approach those for early sealed and uncracked samples (Fig. 4C: S0/S1, S0/S2 and S0/S3 vs S1).

Such results suggest that a good sealer can also be applied with success to concrete that is severely affected by ASR, can stop concrete expansion and even produce contraction, at least for non massive components.

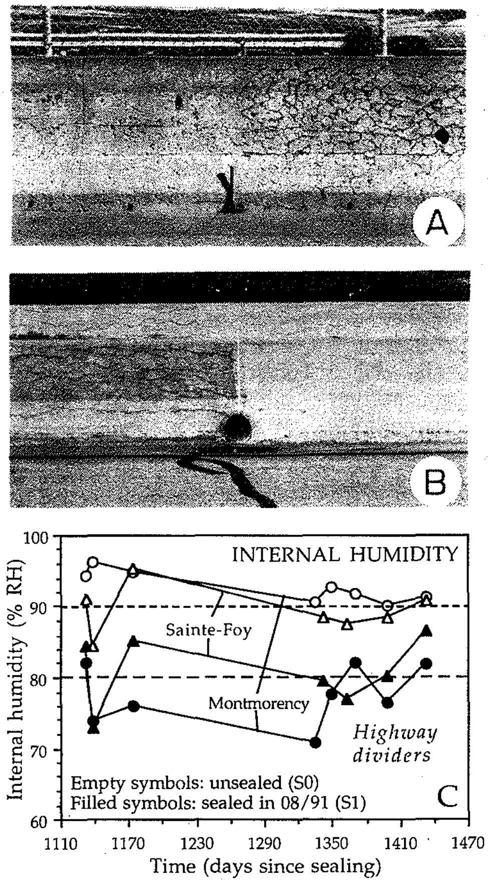

Fig. 5 Unsealed and silane-sealed (S1) sections of highway dividers in Montmorency (A) and in Sainte-Foy (B), and corresponding internal humidity during the last year (C).

Effectiveness of sealers on ASR affected field structures

Only one month after the application of silane S1 on highway dividers, map-cracking was much less apparent than on unsealed sections (no humid brown haloes), regardless of the initial degree of deterioration (Figs 5A,B). At that time, the sections treated with siloxane S2 or S3 still showed a wet appearance, while those treated with silane S6 looked exactly like unsealed concrete. The same remarks apply after 4 years except that siloxane-treated surfaces have progressively dried. However, they still look darker and less uniform than those that were silane-treated. Map-cracking, which has developed significantly in Sainte-Foy over the last 4 years, is much less apparent on sections sealed with silane S1 and siloxanes S2 and S3. From an aesthetic point of view, the silane S1 is the most interesting sealer among those tested, while the other silane S6 is the worst. This suggests that a sealer cannot be selected based only on its formulation.

As for laboratory samples, measurements within the highway dividers indicated that the apparent relative humidity is significantly lower in sections sealed with silane S1 (averages of 78% RH in Montmorency and 82% in Sainte-Foy) than in unsealed control sections (93 and 90% RH, respectively) (Fig. 5C). Since 1994, measurements are made to determine if expansion is also stopped or reduced in the components sealed with silane S1. Due to seasonal variations, the results obtained so far cannot be interpreted.

For mass concrete, a good sealer should not reduce ASR expansion but may reduce the surface deterioration by reducing the effect of exposure conditions such as wetting/ drying and freezing/thawing. However, in the particular case of concrete pavements, some experiments in the USA indicated that even a good silane- or siloxane-based sealer is not effective for a sufficiently long period of time, for various reasons: (1), water penetration is accelerated under pressure developed by tires; (2), evaporation is more difficult because of the presence of water during certain periods of time on the surface of the pavement, and (3), progressive abrasion of the thin layer of sealed concrete.

CONCLUSION

Wetting/drying significantly reduced ASR expansion but promoted map-cracking, while freezing-thawing greatly increased ASR expansion as well as surface cracking. However, in the absence of ASR, wetting-drying and freezing-thawing did not cause damage to concrete, which was air-entrained. This study confirms that the exposure conditions greatly influence the deterioration at the surface of ASR affected concrete.

Whatever the exposure conditions, all silane and siloxanes tested in the laboratory reduced ASR expansion to an acceptable level, and the corresponding samples did not show map-cracking. The epoxy sealer tested was not effective. Linseed oil prevented map-cracking while reducing expansion, however not sufficiently. The results obtained in the laboratory suggest that a good sealer can reduce ASR expansion in new concretes and the related surface cracking as well, at least for members of less than 255 mm in thickness. The laboratory results also indicate that a good sealer can be applied with success to concretes that are severely affected by ASR, can stop concrete expansion and even produce contraction, at least for non massive concrete members. Whatever the exposure conditions, for sealed as well as unsealed samples, all expansion results correlated with mass and humidity variations within the concrete specimens tested.

Based on field experiments, a good sealer, particularly a good silane, can greatly improve the aesthetic appearance of ASR affected concretes, even those showing severe map-cracking. As for laboratory samples, the beneficial effect of sealers correlates with the humidity decrease within the sealed non-massive components, and should also correlate with expansion reduction (measurements in progress). The field experiments also demonstrated that a sealer cannot be selected based only on its formulation.

ACKNOWLEDGEMENTS

This study was supported by the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche du Québec (FCAR), and the National Science and Engineering Research Council of Canada (NSERC). Special thanks to Transport Québec, in particular to D. Vézina and A. Claveau, for their very kind collaboration in laboratory and field works.

REFERENCES

Bérubé, M.A., Frenette, J., Landry, M., McPhedran, D., Pedneault, A. & Ouellet, S. 1994. 'Évaluation du potentiel résiduel de réaction et d'expansion du béton en service atteint de réactivité alcalis-silice', Submitted to Hydro Québec, September 1994, 152 p.

Ludwig, U. 1989. 'Effects of environmental conditions on alkali-aggregate reaction and preventive measures', Proc. 8th Int. Conf. on AAR, eds. K. Okada, N. Nishibayashi & M. Kawamura, July 1989, Society of Materials Science, Kyoto, Japan, 583-596.

Nishibayashi, S., Yamura, K. & Sakata, K. 1989. 'Evaluation of cracking of concrete due to alkali-aggregate reaction', Proc. 8th Int. Conf. on AAR, eds. K. Okada, N. Nishibayashi & M. Kawamura, July 1989, Society of Materials Science, Kyoto, Japan, 759-764.