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LABORATORY ASSESSMENT OF THE POTENTIAL RATE OF ASR EXPANSION OF FIELD CONCRETE

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ABSTRACT

In-situ monitoring of concrete deformations and movements is the best way to assess the current expansion of ASR-affected concrete members. However, monitoring and interpretation of the corresponding results usually takes a few years before it is possible to distinguish between permanent and cumulative deformation due to ASR and cyclic movements related to thermal and climatic variations. Alternatively, laboratory tests on cores are less expensive and more rapid, and are commonly used to assess the potential for further expansion due to ASR. ASR and related expansion and deterioration will continue in an affected concrete structure as long as the reactive mineral phases within the aggregate particles are not completely consumed, and if the two other essential conditions are still satisfied, i.e. high humidity and high alkali concentration in the concrete pore solution. Expansions are also functions of temperature and stress conditions in service. The risk of expansion and damage due to ASR can be reasonably assessed in the laboratory from: (1), the inherent expansivity of the concrete under study, which is determined by testing core samples in air at 100% RH and 38°C; (2), the residual absolute reactivity of the aggregates present in the concrete under study, which can be determined by testing core samples in 1N NaOH solution at 38°C or, even better for coarse aggregates, by testing aggregates extracted from cores through the Concrete Prism Method CSA A23.2-14A-94; (3), the amount of alkalies that are still active in the concrete, e.g. in the pore solution, which is estimated by a hot-water extraction method on ground concrete, and (4), humidity, (5), temperature, and (6), stress conditions (confinement, reinforcement, pretensioning, postensioning,...) in service. The individual risk indices corresponding to each of the above parameters are combined to determine the potential rate of ASR expansion of concrete members in service, either already affected by ASR or not.

Keywords: Alkali-aggregate reaction, concrete cores, expansion tests, humidity, prognosis, soluble alkali content, stress conditions, temperature.

INTRODUCTION

The potential for further expansion due to ASR is important information when planning the schedule for maintenance of affected concrete structures, and selecting the most appropriate techniques 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. In actual fact, "in-situ" measurements often lead to more optimistic results than laboratory tests on concrete cores, which are not tested under the same conditions as in service, particularly concerning environment (temperature, humidity, wetting/drying, freezing/thawing, etc.) and applied compressive stresses. The stress conditions are particularly critical when using cores for investigating mechanical performance and future expansion of concrete affected by ASR. Indeed, these cores are not confined and are usually free of reinforcement. However, in-situ monitoring is usually costly compared to laboratory tests and analysis, 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 "in situ" monitoring.

ASR and associated expansion and deterioration will continue in a concrete structure as long as the reactive mineral phases within the aggregate particles are not completely consumed, and the two other essential conditions are still satisfied, i.e. high humidity and high alkali concentration in the concrete pore solution. Expansions are also functions of temperature and stress levels in service. A methodology is proposed hereafter to estimate the potential rate of ASR expansion of concrete members either already affected by ASR or not. The proposed coefficient PRE (for "Potential Rate of Expansion" due to ASR) takes in account all the following factors, most of them corresponding to a particular coefficient (Fig. 1):

- Residual expansion rate in the laboratory of the concrete under study (coefficient EXP).
- Absolute reactivity of aggregates present in the concrete under study (coefficient ABR).
- Petrographic characteristics of the concrete specimens prior and after expansions tests on cores, for the correct interpretation of the corresponding results (Bérubé et al. 1993).
- Water-soluble alkali content of the concrete under study (coefficient ALK).
- Humidity conditions in service (coefficient HUM).
- Temperature in service (coefficient TEM).
- Compressive stresses applied to the concrete in service (coefficient STR).

RESIDUAL EXPANSION RATE IN THE LABORATORY (EXP)

The coefficient EXP is obtained through expansion tests on cores in air at >95% RH and 38°C, which is considered the most realistic laboratory test procedure to assess the potential for ASR expansion of concrete members in service. Indeed, the concrete specimens are tested with their actual alkali content (no addition such as when testing in alkaline solution, no dilution such as when testing in water). The test procedure is detailed elsewhere (Bérubé et al. 1993, 1994, 1995, Bérubé and Fournier 2000). The annual rate of expansion after mass equilibrium over a testing period of one year or more is used for prediction (Fig. 2). This rate can be qualified in accordance with Table 1, where EXP varies from 0 to 16.

The expansions obtained may be underestimated if the concrete specimens were abnormally fissured or porous compared with the overall concrete member under study. In such cases, some ASR gel formed during the test can expand freely in open voids without causing expansion, the coefficient EXP thus being a minimum. Expansions of 0.003% per year, which is the lower limit considered in Table 1, may appear very low, however may be of importance for the corresponding structure under study. On the other hand, low expansions, let say <0.005% per year, may be not statistically significant considering the precision of the

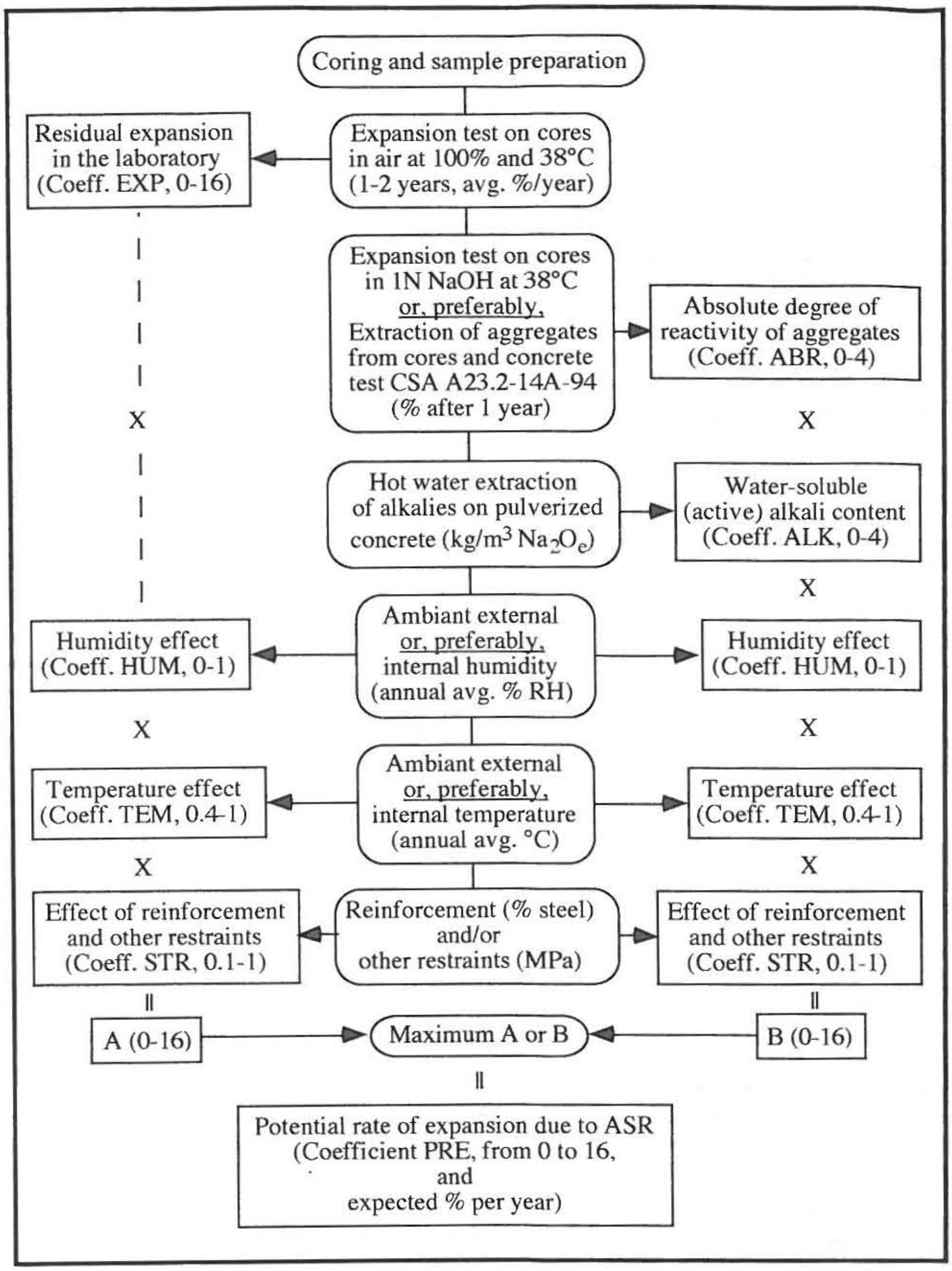

Fig. 1: Laboratory assessment of the potential rate of ASR expansion of concrete members in service either already affected by ASR or not.

TABLE 1: Classification of the Various Coefficients Proposed to Estimate the Potential Rate of ASR Expansion of Concrete Members in Service either already Affected by ASR or not, Based on Laboratory Test Results and Field Conditions.

Coefficient EXP: Residual expansion in the laboratory (core testing in air at >95% RH and 38°C)

% exp./year [1]	Residual exp. [1]	EXP [1]	% exp./year [1]	Residual exp. [1]	EXP [1]
< 0.003	negligeable	0	0.015 to 0.02	moderate	6
0.003 to 0.005	very low	1	0.02 to 0.025	high	9
0.005 to 0.01	low	2	0.025 to 0.03	high	12
0.01 to 0.015	moderate	4	> 0.03	very high	16

Coefficient ABS: Absolute reactivity of aggregates (core testing in 1N NaOH at 38°C or Concrete Prism Test CSA A23.2-14A on aggregates extracted from cores)

% exp. at 1 year [1]	Reactivity [1]	ABR [1]	% exp. at 1 year [1]	Reactivity [1]	ABR [1]
< 0.04	negligeable	0	0.12 to 0.20	high	3
0.04 to 0.08	low	1	> 0.20	very high	4
0.08 to 0.12	moderate	2			

Coefficient ALK: Water-soluble alkali content (hot-water extraction method)

$kg/m^3\ Na_2O_e$	Alkali content	ALK	$kg/m^3\ Na_2O_e$	Alkali content	ALK
< 1.0	very low	0	2.0 to 2.5	high	3
1.0 to 1.5	low	1	> 2.5	very high	4
1.5 to 2.0	moderate	2			

Coefficient HUM: Humidity conditions in service (internal or external)

Internal humidity	"Humidity risk"	HUM	Internal humidity	"Humidity risk"	HUM
< 80% RH	very low	0	90-95% RH	high	0.75
80-85% RH	low	0.25	95-100% RH	very high	1
85-90% RH	moderate	0.5			

External (ambiant) humidity	Thin element (<0,5 m)		Thick element (>0,5 m)	
	"Humidity risk"	HUM	"Humidity risk"	HUM
Indoor • <70% RH	very low	0	low	0.5
• 70-80% RH	low	0.25	moderate	0.75
• 80-90% RH	moderate	0.5	high	1
• 90-95% RH	high	0.75	very high	1
• 95-100% RH or immersed	very high	1	"	1
Outdoor in deserts • Not in contact with the ground	very low	0	moderate	0.5
• In contact with the ground	low	0.25	high	0.75
Outdoor in other areas in North America				
• Not exposed to rain nor in contact with the ground	moderate	0.5	high	0.75
• Not exposed to rain but in contact with the ground	high	0.75	very high	1
• Exposed to rain, immersed or buried	very high	1	"	1

Coefficient TEM: Temperature conditions in service

Annual avg. temp. (°C)	TEM	Annual avg. temp. (°C)	TEM	Annual avg. temp. (°C)	TEM
< 0	0.4	10 to 20	0.7	> 30	1.0
0 to 10	0.55	20 to 30	0.85		

Coefficient STR: Reinforcement and other restraints in service (in the direction(s) of rebars or restraints)

% of steel	STR	% of steel	STR	Restraint (MPa)	STR	Restraint (MPa)	STR
0	1.0	1	0.3	0	1.0	1	0.4
0.25	0.75	2	0.25	0.25	0.85	1.5	0.3
0.5	0.55	≥ 3	0.2	0.5	0.7	2	0.2
0.75	0.4			0.75	0.55	≥ 3	0.1

Coefficient PRE: Potential rate of ASR expansion in concrete members in service

PRE	Qualification	PRE	Qualification	PRE	Qualification
0	negligeable	1 to 2	low	>6 to 12	high
> 0 to 1	very low	2 to 6	moderate	>12 to 16	very high

[1] After mass equilibrium when testing cores; the value is considered a minimum if the concrete cores were abnormally fissured or porous compared to the overall concrete member under study (coefficients EXP and ABS) or quite impermeable to the alkaline solution (coefficient ABS).

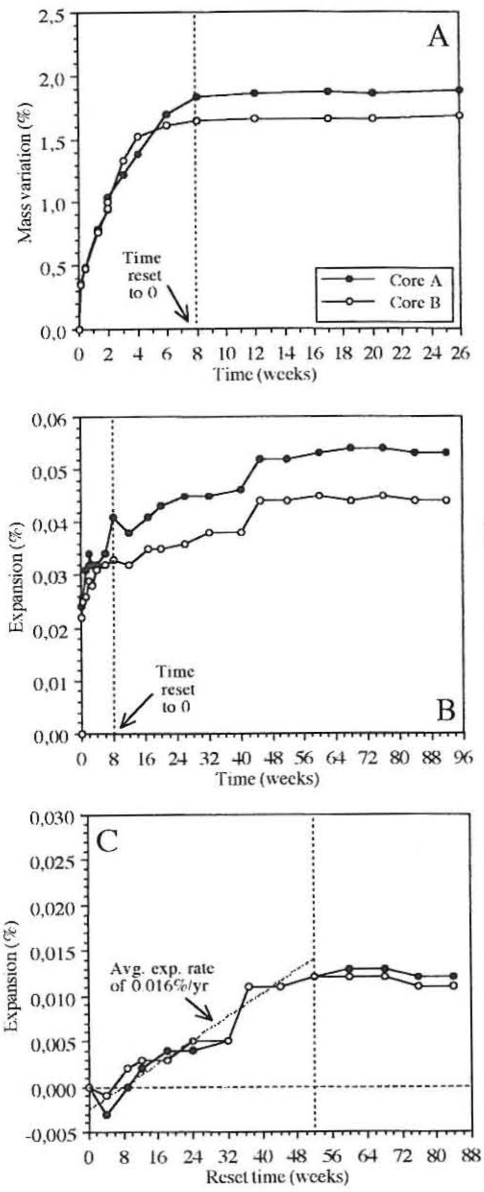

Fig. 2: Results from expansion tests in air at >95% RH and 38°C on core samples from a dam in Québec (Canada). A) Mass variation. B) Expansion. C) Reset expansion (after mass equilibrium).

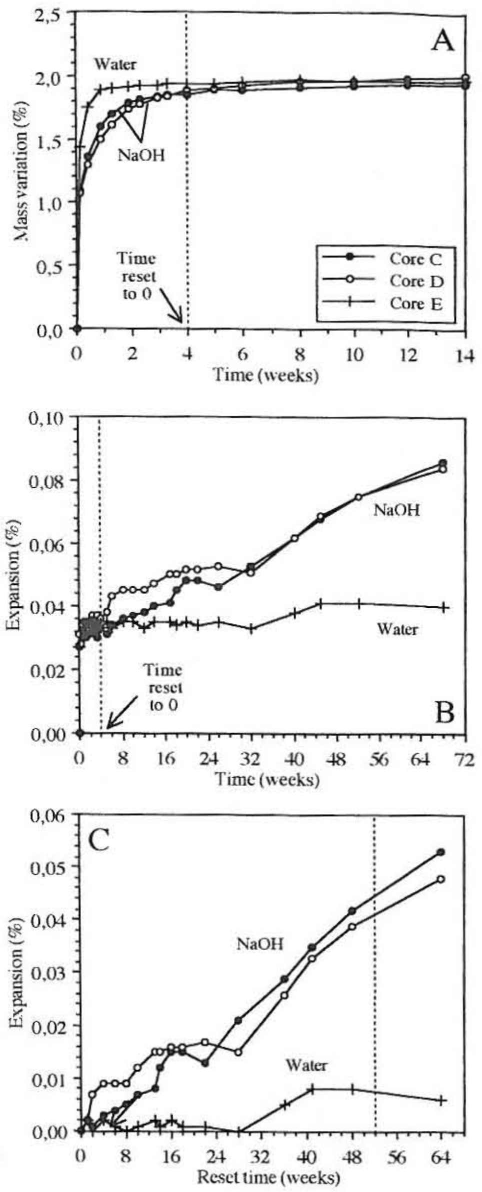

Fig. 3: Results from expansion tests in 1N NaOH and water at 38°C on core samples from a dam in Québec (Canada). A) Mass variation. B) Expansion. C) Reset expansion (after mass equilibrium).

expansion measurements, which is estimated to ±0.005%. In this respect, a regression analysis may help in improving the statistical significance of relatively low expansion values (see Fig. 2C). In any case, when the coefficient EXP is relatively low, which could be attributed to various reasons (test precision, preexisting fissuration, porosity,...), in the further calculation of the overall coefficient PRE, it is replaced by the product of the two coefficients ABR ("Absolute reactivity of aggregates") and ALK ("Water-soluble alkali content") (Fig. 1). On the other hand, significant expansions do not necessarily mean that the concrete under study will expand in service, for instance if the humidity conditions in the field are too low to sustain ASR and/or the stresses are sufficiently high in the concrete in service to suppress expansion. On the other hand, low expansions should indicate that the concrete under study should not expand in service unless the concrete specimens tested are more fissured and/or more porous than the overall concrete in this member.

Let us recall that the size (diameter) of the cores tested may affect the expansion rates. In general, smaller cores expanded at higher rates in the short term while larger cores expanded significantly more in the long term, let say after one year or more (Bérubé et al. 1994). However, the differences in the long term are not high enough to apply a correction for the core diameter.

ABSOLUTE REACTIVITY OF AGGREGATES (ABR)

The coefficient ABR can be obtained by conducting expansion tests on cores in 1N NaOH at 38°C, using the procedure detailed elsewhere (Bérubé et al. 1993, 1994, 1995, Bérubé and Fournier 2000) or, even better for coarse aggregates, by performing standard concrete prism tests CSA A23.2-14A on aggregates extracted from cores after a number of accelerated cycles of freezing in liquid nitrogen and thawing in a microwave oven, using the procedure detailed elsewhere (Pedneault 1996, Bérubé et al. 1995, 1996a, Bérubé and Fournier 2000). The latter procedure was first proposed by Grattan-Bellew and Danay (1995) and proved to be reliable (Pedneault 1996). Let us mention that the CSA concrete may depart from the concrete under study with regards to reactive aggregate content, aggregate size, air content and/or water/cement, which all affect ASR expansion at some extent when testing in air at 100% RH and 38°C (Bérubé et al. 1994). On the other hand, expansions in NaOH, at least during about the first 6 months of testing, are also significantly affected by many parameters such as core diameter, concrete alkali content, water/cement, permeability, porosity, and preexisting fissuration (Bérubé et al. 1994), which are all controlled in the CSA test. For instance, a larger core diameter, a lower alkali content, or a lower water/cement retards the expansion in the short term in 1N NaOH. By extending the tests to one year, the effects of all three above parameters are minimized. However, significant amounts of reactive silica can be released in the NaOH solution rather than produce expanding gels, particularly with high-permeability concretes (Pedneault 1996).

The expansion obtained after one year, after mass equilibrium when testing cores (Fig. 3), can be qualified in accordance with Table 1, with the coefficient ABR ranging from 0 to 4. However, the expansions measured in the tests may be underestimated if the concrete specimens tested were abnormaly fissured or porous compared to the overall concrete member under study, since some ASR gel formed during the test may have expanded freely in open voids without causing expansion, or some reactive silica may have migrated in the NaOH solution, or if the concrete tested is quite impermeable. In such cases, the coefficient ABR is considered as a minimum. Significant expansions in NaOH do not necessarily mean that the corresponding concrete will expand in service, which will not take place for instance if the humidity conditions in service and/or the concrete alkali content are too low to sustain ASR. On the other hand, low expansions should indicate that the aggregates are not susceptible to ASR unless the concrete under test is highly fissured or porous or quite impermeable to the alkaline solution (low-permeability concrete).

WATER-SOLUBLE ALKALI CONTENT (ALK)

The alkali concentration in the pore solution of ASR-affected concretes tends to progressively decrease with time, being incorporated in the reaction products (Bérubé et al. 2000a). A treshhold around 0.6 M [OH^-] or [NaOH+KOH] in the long term has been observed by Duchesne and Bérubé (1994a) under which no significant expansion was observed in the long term for laboratory concretes made with very reactive aggregates from Canada. The residual amount of alkalies in solution may then appear to be a very attractive parameter for assessing the potential for future ASR in concrete, provided that it can be measured accurately. Unfortunately, it is difficult to extract under high pressure the pore solution of aged concretes. However, it is possible to determine, using the hot-water extraction method described by Bérubé et al. (2000a, 2000b), the amount of alkalies that were originally in the pore solution before the concrete was dried for the measurements, on a kg/m^3 Na_2O_e basis. The alkali concentration in the pore solution could then be estimated knowing this water-soluble alkali content and the original water content of the concrete (Bérubé et al. 2000a).

However, the measured water-soluble alkali content must be corrected to take in account the alkali contribution by the aggregates during the test. This contribution varies greatly from one aggregate to another, from 0.3 to 1.6 kg/m^3 Na_2O_e in the study by Bérubé et al. (2000a). The corrected water-soluble alkali content can then be qualified in accordance with Table 1, with the coefficient ALK ranging from 0 to 4. The value considered as totally safe with respect to ASR (i.e. <1.0 kg/m^3 soluble Na_2O_e) corresponds to a total alkali contribution by the cement of about 1.5 to 2.0 kg/m^3 Na_2O_e (Bérubé et al. 2000a). Indeed, significant amounts of alkalies from the cement, about 40% in the case of normal portland cements, are incorporated in the cement hydrates (Duchesne and Bérubé 1994b). This explains why the total alkali content supplied by the cement (= cement factor x cement alkali content) is generally higher than the water-soluble alkali content. However, some alkalies may be supplied by other concrete constituents and by external sources, may be progressively entrapped in the products from ASR, may migrate in or out of the sampled concrete zones, may concentrate by evaporation near the concrete surface and/or may be leached from this surface or along cracks by rain or running water. As discussed by Bérubé et al. (2000b), it is recommended that the alkali measurements be performed on cores taken at sufficient depths inside the concrete members under study.

Unfortunately, as discussed by Bérubé et al. (2000a), the experimental variability of the test method appears too high to follow the progress of ASR from year to year in a given concrete structure. Significant amounts of alkalies are effectively incorporated in the ASR products and are not leached out in the hot water extraction method. However, it was not possible to determine how much alkalies incorporated in ASR products are released in the test procedure, if some are effectively released (Bérubé et al. 2000a). The water-soluble alkali content would then be overestimated if certain amounts of alkalies are effectively leached out of the ASR reaction products in the test method.

HUMIDITY CONDITIONS IN SERVICE (HUM)

Commercial probes can be used to measure humidity inside concrete members along small drillholes (Bérubé et al. 1994, 1995, 1996b, Stark 1991). Some experiments suggest that a minimum internal humidity of 85% RH is required at 38°C to sustain ASR in concrete made with very reactive aggregates and high alkali contents (Bérubé et al. 1996b). Another study indicated that the same concrete developed significant expansion at 38°C even when exposed to external humidity of 70% RH, and that the less reactive the aggregate, the higher the critical ambiant humidity level required for significant expansion due to ASR (Bérubé et al. 1994, Pedneault 1996). Also, according to Olafsson (1987), the higher the temperature, the lower this critical level. A distinction must then be made between internal and external humidity, with different minimum levels for ASR being used accordingly. The humidity conditions can be qualified with respect to the risk for ASR in accordance with Table 1, where the coefficient

HUM ranges from 0 to 1. This coefficient takes in account the fact that the humidity inside thick concrete members tend to remain higher than inside thin members, which makes the former less influenced by the external humidity conditions.

TEMPERATURE IN SERVICE (TEM)

The expansion tests described above are performed at 38°C while most concrete structures exposed outdoor in North America are submitted on a yearly basis to lower temperatures, for instance to 7°C on an average in the Montréal area, in Canada. On the other hand, the higher the temperature, the greater is usually the expansion rate due to ASR, while the ultimate expansion is not necessarily greater. The coefficient TEM is proposed to take in account the effect of temperature (Table 1).

COMPRESSIVE STRESSES IN SERVICE (STR)

In general, internal (pre-tensioning, reinforcement, confinement,...) as well as external (post-tensioning, loading, structural efforts,...) compressive stresses applied to concrete can significantly reduce ASR expansion, however not always the surface cracking. It is then realistic to apply a correction to the results obtained from expansion tests on cores that are free from stress. The coefficient of correction STR is, however, the most difficult parameter to estimate because of the very limited amount of relevant information. Moreover, one can expect that a same level of reinforcement, for instance, should be more effective in the presence of a marginally reactive aggregate than with a very reactive one. The values proposed in Table 1 must then be considered with circumspection. They correspond to the median results found in a report by the Institution of Structural Engineers (1992).

When rebars are installed on a single plane in the concrete member (1D or 2D, depending if all bars are parallel or at right angle) or on many parallel planes (2D or 3D, again depending if all bars are parallel or at right angle), but without any anchorage between the different planes, the coefficient STR applies in the direction(s) of the rebars, while expansion could even be higher in the other direction(s) compared to no reinforcement at all. In the same way, in the cases of uniaxial (1D) or biaxial (2D) compressive stresses, STR applies in the direction(s) of the stresses, while expansion could even be greater in the other direction(s) compared to no restraint at all.

POTENTIAL RATE OF ASR EXPANSION IN SERVICE (PRE)

The coefficient PRE is proposed as an estimate of the "<u>P</u>otential <u>R</u>ate of <u>E</u>xpansion" due to ASR of concrete members in service either already affected by ASR or not. This coefficient takes in account all above coefficients. As illustrated in Fig. 1, it is obtained as it follows:

PRE = (maximum [EXP] <u>or</u> [ABR x ALK]) x HUM x TEM x STR

For the reasons mentioned before (mainly test precision), the coefficient EXP is replaced by the product of the two coefficients ABR and ALK, when this product is greater. EXP varies from 0 to 16 while both ABR and ALK vary from 0 to 4, with their product then also vaying from 0 to 16. The overall coefficient PRE also varies between a minimum of 0 and a maximum of 16. In accordance with Table 1, the potential rate of ASR expansion in the concrete member under study can be qualified from negligeable to very high. The sign $\geq$ which may apply for the coefficients EXP and ABR also apply in the calculation of PRE, the value obtained then corresponding to a minimum.

The coefficient PRE gives a qualitative indication of the potential rate of ASR expansion of concrete members in service. This qualitative coefficient index would be of greater interest if combined with an expected absolute rate of expansion. Unfortunately, the information is very limited relating the results obtained in the laboratory with those observed in service. However, after the above methodology had been applied to a number of Hydro-Québec dams, it appears realistic to use the same classification as for the above coefficient EXP, which corresponds to Fig. 4. In other words, the assumption is made that the expansion rate in service (PRE) will be quite similar to the one observed in the laboratory (EXP) when the following conditions are satisfied in service: (1), very high humidity conditions (i.e. HUM = 1); (2), temperature over 30°C (i.e. TEM = 1), and (3), no rebar neither compressive stresses applied to concrete (i.e. STR = 1).

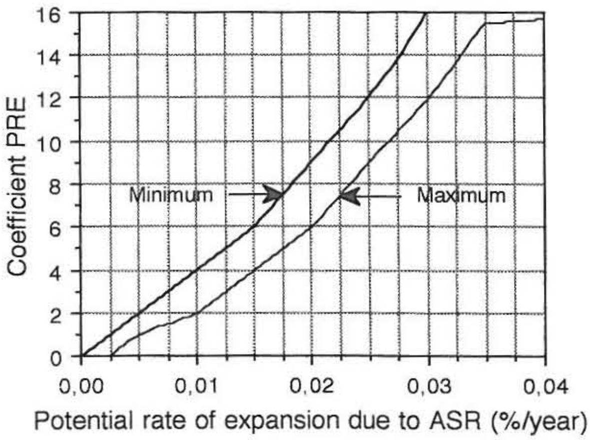

Fig. 4: Approximation of the potential rate of ASR expansion in field concrete as a function of the coefficient PRE (Potential Rate of Expansion due to ASR).

CONCLUSION

The coefficient PRE takes in account many parameters which affect, to some extent, the rates of ASR reaction and expansion. It takes a zero value when at least one of the three necessary conditions for ASR is not satisfied, e.g. when the aggregates are not reactive, when the concrete alkali content is low, or when the humidity conditions in service are low. Also, it can predict the anisotropic expansion in members whose different parts are exposed to different humidity, temperature and/or stress conditions. However, it does not predict for how long the expansion will continue in the concrete structure but just gives an indication of the maximum current or future rate of expansion due to ASR. It must be also emphasized that the coefficient PRE is mostly based on laboratory results. For sure, in the final evaluation, all other relevant available informations such as the age of the structure, the present state and the progress of deteriorations, the rates of expansion and deformation, the behaviors of similar structures made with the same types of aggregates, and modelling studies, have to be considered. As mentioned before, long-term monitoring is the only way to obtain relevant information on the current rates of expansion, which can then be extrapolated.

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