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MECHANICAL BEHAVIOR OF CONCRETE AFFECTED BY ASR

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ABSTRACT

Concretes were prepared with 2 limestone aggregates, highly reactive and non reactive with respect to ASR. They were stored at 23°C and 38°C, in air at 100% R.H. and in a NaCl solution, and tested at different times for longitudinal expansion, mass variation, ultrasonic pulse velocity, uniaxial compressive strength and indirect tensile strength. The effects of ASR on the fundamental mechanical properties of these concretes are presented in this paper.

1. INTRODUCTION

In Quebec (Canada), limestones are intensively used as concrete aggregates and some varieties are alkali-silica reactive. An experimental project initiated in 1986 between Laval University and Hydro-Québec [1] deals with the effects of temperature, wetting/drying, freezing/thawing and deicing salts on ASR, the mechanical performance of affected concrete, and the repairs techniques. This paper summarizes the results concerning the fundamental mechanical properties of concrete samples affected by ASR and the effects of temperature and NaCl.

2. EXPERIMENTAL

Concrete samples were prepared with two fine-grained limestone aggregates with similar mechanical properties but highly reactive and non reactive in concrete, with respect to alkali-silica reactivity. The reactive one was a siliceous and slightly dolomitic limestone from the Spratt quarry, (Ottawa, Ontario, Canada). It was supplied by the Ministry of Transportation of Ontario. The non reactive limestone was from the Limeridge quarry (Sherbrooke, Quebec, Canada). These two rocks were used as coarse aggregate, with the following grading: 0% retained on 3/4" (19,1 mm) sieve, 40% on 1/2" (12,7 mm), 30% on 3/8" (9,53 mm) and 30% on no.4 (4,75 mm). A non reactive natural sand was used as fine aggregate. A normal Portland cement (ASTM Type I), containing 0,96% total alkalies (Na_2O equiv.), was used. Alll mixes had a W/C ratio of 0,5 and a cement content of 350 kg/m^3. The proportions of fine and coarse aggregates were 40% and 60% by mass, respectively. The slump was between 110 and 150 mm, and the air content ranged from 2,9% to 3,6%. A ligno-sulfonate salt (chlorine free) was used as water reducer (4,65 ml/kg of cement). The total alkali content of all mixes was increased to 1,25% of the cement mass (Na_2O equiv.) by adding NaOH to the mix water, thus giving 4,4 kg (alkalies)/m^3 of concrete.

For each set of storage conditions: (1) air at 100% R.H. and 23°C, (2) 6% NaCl solution at 23°C, (3) air at 100% R.H. and 38°C, and (4) 6% NaCl solution at 38°C, concrete specimens of various sizes were cast: 150 mm dia. x 300 mm cylinders (compressive strength), 100 mm dia. x 200 mm cylinders (Brazilian indirect tensile strength), and 100 mm x 100 mm x 250 mm prisms (non-destructive testing). After 7 days of moist curing at 23°C, the concrete specimens were stored into plastic sealed containers at a relative humidity of 100% (or nearly so), or immersed in a 6%

(by mass) NaCl solution (in the same type of containers). The containers were then stored at room temperature (≈ 23°C) or in a controlled heated room (38 ± 2°C).

Non-destructive testing (on prisms) was performed at 0, 1, 2, 4, 8, 12, 16, 20, 24 weeks after initial curing, and then at 8 weeks intervals. Tests included length and mass changes, and ultrasonic pulse velocity (PUNDIT). Each non-destructive result presented hereafter is the average value for 4 prisms. Destructive tests (on cylinders), including uniaxial compressive strength (ASTM C39), Brazilian splitting tensile strength (ASTM C496), and modulus of elasticity (ASTM C469), were performed after 28 days, 3, 6, 12 and 24 months. For the compressive test, a load cell and two LVDT strain gages were plugged to a microcomputer data acquisition system which automatically records the stress-strain relationship. For the tensile test, only the ultimate strength value was recorded. Each destructive result presented hereafter is the average value for 3 cylinders.

3. RESULTS AND DISCUSSION

3.1 Non-destructive Testing

The length change and ultrasonic pulse velocity results are given on Figures 1 and 2. The maximum expansions at 1 year (specimens in air at 100% R.H. and 38°C) are 0,26% with Spratt and 0,02% with Limeridge aggregates. This is in good agreement with the known potential of alkali-reactivity of the two aggregates. As already observed [2,3], the ultrasonic pulse velocity appears much less sensitive to ASR, the larger difference (at 2 years) between the two concretes being less than 10% with respect to the initial value (Fig. 2). A reverse conclusion has been drawn by Swamy & Al Asali [4] for laboratory concretes containing opal and fused silica as partial replacement of fine aggregates. However, a UPV technique remains of interest for evaluating concretes in service which are severely deteriorated by ASR [5,6,7,8]. The maximum gains of mass presented by the concrete specimens were obtained in air at 100% R.H. and 38°C, but the differences between the reactive and the sound concrete were not significant (maximum gain of 56 g at 2 years with Spratt while 32 g with Limeridge aggregates), for a maximum difference of only 0.4% of the total mass of the specimens (6 kg), which is too small to clearly discriminate between sound and ASR affected concretes. This observation does not agree with the results by Swamy & Al Asali [9], however for concretes with the reactive phases in the fine portion of the aggregates.

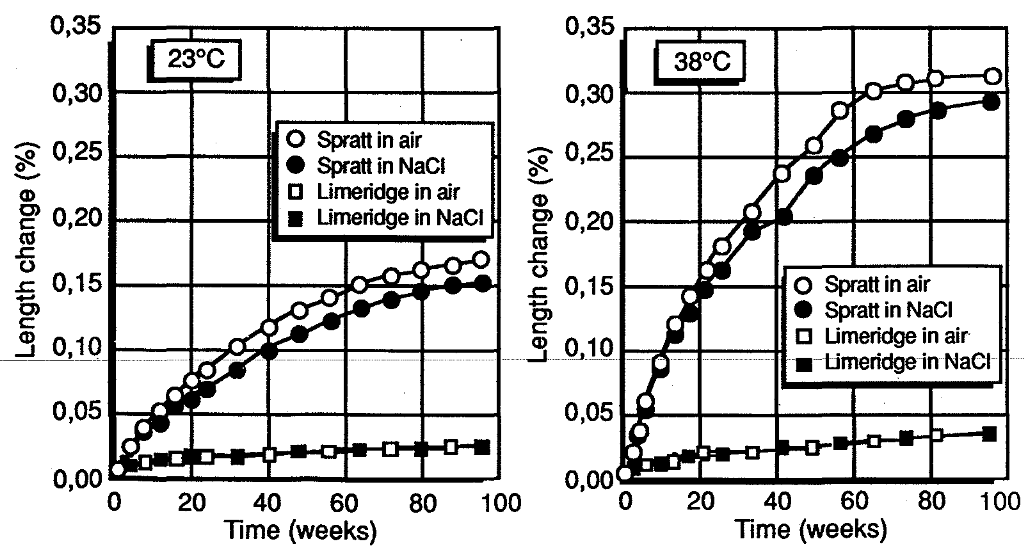

Figure 1 — Length changes (longitudinal expansions) of concrete specimens vs time.

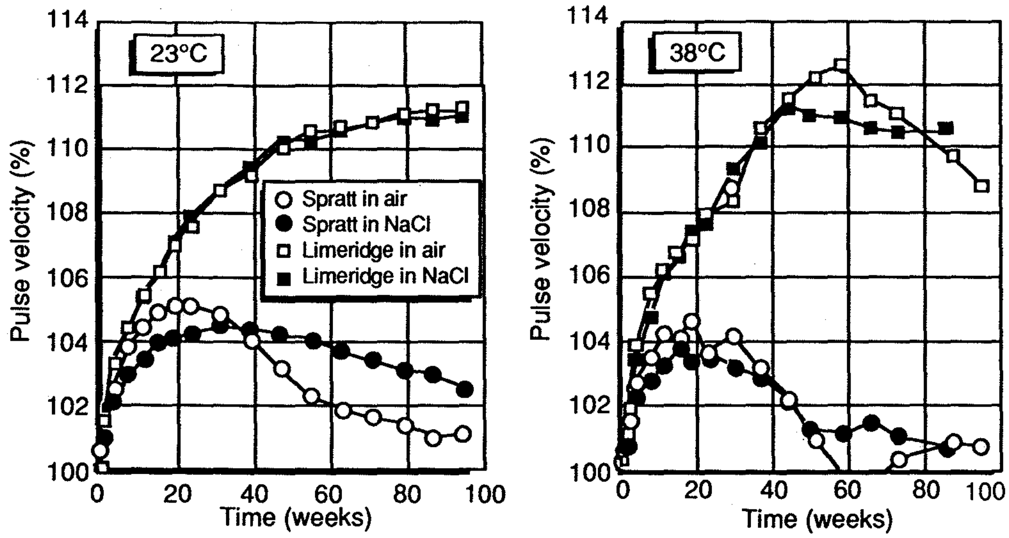

Figure 2 — Ultrasonic pulse velocity (PUNDIT) in concrete prisms (% of initial value) vs time.

Figures 1 and 2 also point out the influence of temperature and NaCl solution. The expansions suffered by the reactive concrete at 38°C are about twice those observed at 23°C (Fig. 1), with higher initial rates of expansions, as already observed [9]. However, the ultrasonic pulse velocity is quite similar at both storage temperatures (Fig. 2), while the mass increases of the specimens were slightly greater at 38°C by only about 10 g or less (on a total of 6 kg). However the results of all non-destructive tests are very similar in air at 100% R.H. and in a 6% NaCl solution. This is likely explained by the fact that such a solution presents a total alkali content (Na2O equiv.) which approaches the one of the concrete pore solution in the samples stored in air, already rich in alkalies. In other words, the NaCl solution is in equilibrium with respect to alkalies with the pore solution that is naturally generated after a few days in such high-alkali concretes.

3.2 Destructive Testing

Typical stress-strain curves for samples stored in air at 100% R.H. and 38°C appear on Figure 3. At 28 days, the curves are similar for both aggregates, thus confirming that the mechanical properties of these aggregates are close. Between 28 days and 1 year, concrete with Limeridge aggregates presents an usual behavior, the compressive strength increasing by about 10% due to additional hydration. However, the variations between 28 days and 1 year are impressive for the reactive concrete: the strength dropped to almost half of its initial value, while the maximum strain is increased by nearly 30%. At a given compressive stress, let say 20 MPa, the strain is 4 times the one for the sound concrete. This clearly shows that ASR affected concretes can suffer much more deformation than sound concrete. Blight et al. [6] effectively observed that such concretes present deformations (at a 15 MPa compressive stress) that may reach 3 times those for sound concretes, while long term strain deformations (creep) may be 2.5 to 4 times greater.

The variations with time of the compressive strength for specimens stored in air at 100% R.H. and 38°C are given on Figure 4. For the reactive concrete, after a slight increase up to 12 weeks, an important loss of strength occurs up to 1 year, e.g. only after significant expansions (>0.1%), to slightly increase after. Such a behavior has already been observed [4,9]. The maximum loss in strength (at 1 year) is about 45% of the maximum value obtained at 12 weeks (50% with respect to the sound concrete, at 1 year). So important losses (≥50%) have also been observed for laboratory concretes [4,9] as well as for concretes in service [6] affected by ASR.

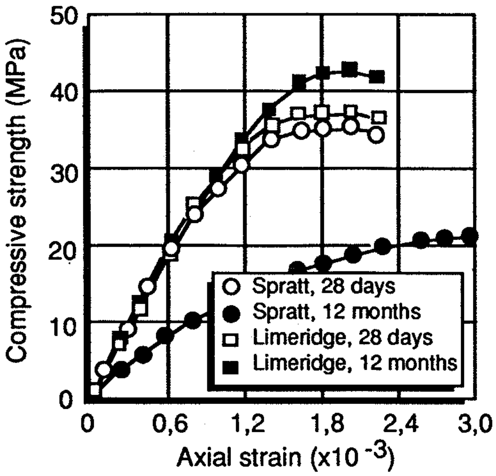

Figure 3 — Typical stress-strain curves for concretes stored in air at 38°C.

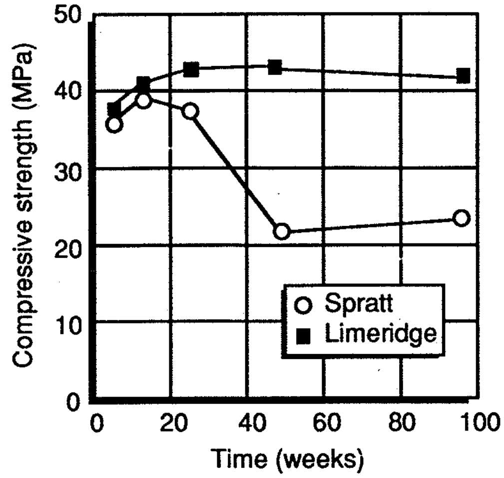

Figure 4 — Compressive strength vs time for concretes stored in air at 38°C.

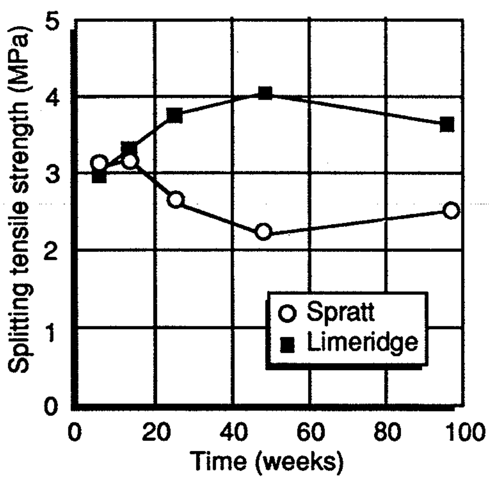

Figure 5 — Tensile strength vs time for concretes stored in air at 38°C.

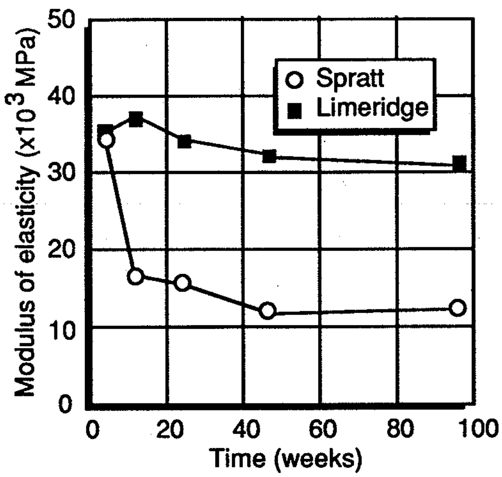

Figure 6 — Modulus of elasticity vs time for concretes stored in air at 38°C.

Figure 5 shows the splitting tensile strength versus time for specimens stored in air at 100% R.H. and 38°C. The sound concrete shows a slight increase in strength, to reach approximately 135% of the initial value. For the reactive concrete, the tensile strength starts to drop after 12 weeks, up to 1 year, and slightly increases after. The total loss (at 1 year) is about 30% of the initial value (45% with respect to the sound concrete, at 1 year). This behavior is roughly similar to the one for the compressive strength, with quite similar losses, also occurring at about the same time (between 12 weeks and 1 year). Thus the ratio between tensile strength and compressive strength is relatively constant and normal at any time (0,07 to 0,11), even slightly but significantly increasing with time. This indicates that the tensile strength of ASR affected concrete is not always more affected than the compressive strength. This observation is in good agreement with another experimental study [2,3], and with field investigations on concrete structures built with limestones [5] and volcanic rocks [8]. However, Blight et al. [6] observed that the tensile strength is much more affected than the compressive strength. For laboratory concretes containing opal and fused silica, Swamy & Al Asali [4,9] drew the same conclusion. These authors also observed, contrarily to the present study, that the splitting tensile strength is affected more and much earlier than the compressive strength, even at very low expansions (<0,01%).

Figure 6 shows the modulus of elasticity versus time for concretes stored in air at 100% R.H. and 38°C. The values are computed from the stress-strain curves (ASTM C496). The results indicate that the sound concrete shows a quite constant modulus of elasticity, (the slight decrease observed with time being possibly related to the relatively high storage temperature; see Table 1). However, for the reactive concrete, this modulus exhibits an important drop (>50%) between 4 and 12 weeks, (i.e. when the compressive and the tensile strengths are still increasing), to slightly decrease until 1 year (for a maximum loss of about 65%), then reaching a relative equilibrium. Note that expansions at 4 and 12 weeks are already important (0,05% and 0,12%, respectively) but these are apparently not enough to affect the strength. These results are quite in good agreement with many other studies which also established that the modulus of elasticity is more affected than the strength [2,3,4,6,9]. In addition, Swamy & Al Asali [4,9] also observed that the modulus of dynamic elasticity is affected at early stages, but prior to any significant expansions.

Concerning the fundamental properties of concrete samples affected by ASR, the quite stable behavior or the slight increase observed in the present study after one year, corresponds to relatively low rates of expansion (slope on Fig. 1). It could indicate that reactions are significantly reduced in the concrete, if not completed, while hydration is likely still continuing, as already suggested in the case of laboratory concrete [3,4,9] and concrete in service [10] affected by ASR.

Table 1 — Summary of destructive testing after one year.

	Spratt aggregate				Limeridge aggregate			
Storage medium	length change (%)	compr. strength (MPa)	tensile strength (MPa)	mod. of elasticity (MPa)	length change (%)	compr. strength (MPa)	tensile strength (MPa)	mod. of elasticity (MPa)
Air at 100% R.H. and 23°C	0,130	29,6	2,4	11 190	0,015	44,9	3,9	35 500
6% NaCl solution at 23°C	0,110	25,8	2,3	7 580	0,014	45,1	4,0	32 150
Air at 100% R.H. and 38°C	0,259	21,2	2,3	11 270	0,021	42,4	4,0	31 145
6% NaCl solution at 38°C	0,236	21,3	1,9	8 273	0,020	42,2	3,8	28 200

The results of destructive tests for the other storage conditions are summarized in Table 1. The compressive strength of the sound concrete is just slightly higher at 23°C. For the reactive concrete, a lower temperature resulted in lower rates of expansion and microcracking, thus in lower decreasing rates of compressive and tensile strengths, and of the modulus of elasticity. For instance, at one year, the specimens stored at 23°C present higher strengths than those stored at 38°C, with still a normal ratio (0,08 to 0,11) between tensile and compressive strengths. However, at one year, the modulus of elasticity of the reactive concrete is similar at both storage temperatures. This is in good agreement with the fact that this modulus is mostly reduced before reaching expansions of 0,1%, this occurring very soon (<12 weeks) for samples stored at 38°C, but also before 1 year for those stored at 23°C. However, in the case of the sound concrete, this modulus appears to be slightly reduced by 10 to 15% at 38°C. This could be explained by differences in the cement paste microstructure (temperature effect). The specimens stored in a 6% NaCl solution perform quite similarly to those stored in air at 100% R.H. (Table 1), but their modulus of elasticity appears to be still more affected, even for the sound concrete.

4. CONCLUSION

Concrete samples were prepared with two fine-grained limestone aggregates with similar physico-mechanical properties, but respectively reactive (0,26% expansion at one year in air at 100% R.H. and 38°C) and non reactive (0,02% expansion at the same conditions), with respect to alkali-silica reactivity. The specimens were stored at 23°C and 38°C, in air at 100% R.H. and in a 6% NaCl solution. Measurements of the mass variations of the specimens and of the ultrasonic pulse velocity (PUNDIT) could not clearly distinguish the ASR affected concrete from the sound concrete. In air at 100% R.H. and 38°C, the non reactive concrete slowly improved its uniaxial compressive and Brazilian splitting tensile strengths, while the reactive samples presented strength increases up to 12 weeks, then 50% strength losses between 12 weeks and 1 year, (i.e. only after 0,12% of expansion), to slightly increase after, (when the expansion rates became relatively low, while the cement hydration was likely still going on). The ratio between the tensile and the compressive strengths was always normal (0,07 to 0,11), even increasing with time, confirming that the tensile strength was not more affected than the compressive strength. However, the modulus of elasticity for the expansive concrete was reduced by more than 50% between 4 weeks (expansion = 0,05%) and 12 weeks (expansion = 0,12%), prior to any loss in strength, to slowly decrease until 1 year (maximum loss of about 65%), before to slightly increase after. This confirms that this modulus is more rapidly affected by ASR than the strength, and that concrete affected by ASR may slightly reinforce again at long term, when the reaction and/or the expansion rates are reduced. At 23°C, the same behaviors were observed, however at lower rates, if we except the fact that a higher storage temperature (38°C) slightly reduced the modulus of elasticity of the sound concrete. Relatively to total alkalies, the 6% NaCl solution was assumed to be approximately in equilibrium with the concrete pore solution, this explaining why the results were relatively similar in air and in NaCl, except for the modulus of elasticity which seems more affected in NaCl. These results are in good agreement with some other studies but are not with other ones. Then, as already suggested [9], the mechanical behavior of concretes affected by ASR could be function of the particular reactive aggregate under test.

5. REFERENCES

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