ALKALI-AGGREGATE REACTION STRUCTURAL EFFECTS: AN EXPERIMENTAL STUDY

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Strains and expansions were measured on concrete made with a famous french reactive aggregate (Chambon dam aggregates). NaOH or KOH was added to the concrete mixes to accelerate the AAR. After one year, the expansions reach 4 ‰. Strains and expansions are showed to be more important, after 3 months, for concrete with added KOH, while they are more important after 6 months for concrete with added NaOH. No influence on concrete compressive strengths and tensile strengths were recorded. However, important Young elasticity modulus losses (40 to 50 %) were measured. An increase of the gel alkali content with time was also observed.

INTRODUCTION

This paper deals with the structural effects of alkali-aggregate reaction (AAR) on the concrete mechanical behavior. The experiments were conducted on different types of reinforced beams, prisms, cylinders and bars stored at 20°C or 40°C and 100% RH. To accelerate the development of the AAR, NaOH or KOH was added in some concrete mixes. The used aggregates are those used for the Chambon dam in the french Alps; one of the most famous french AAR case (Groupe de travail I.T.B.T.P. (1)). No addition of other reactive aggregates, such as opal, was made allowing a comparison of our results (cracking and gel exudation related to internal chemical reactions) with those recorded in the Chambon dam. The compressive strengths, tensile strengths and elasticity modulus were measured at 1, 3, 6 and 12 months. Moreover, the samples were observed with a scanning electron microscope (SEM) after 1, 3, 6 and 12 months. The gels were analyzed with the coupled Energy Dispersive X-Ray Analysis system (EDXA).

EXPERIMENTAL

The used aggregates are muscovite gneiss collected in the quarry where the aggregates of the Chambon dam were sampled. These aggregates are classified as reactive in the test proposed by Ranc et al (2) and Sorrentino et al (3). The following sizes were obtained: 0/5, 5/12.5, 12.5/20. The cement is a CPA 55 Portland cement with 0.917 Na_2O eq. (Table 1). The water/cement ratio is 0.5; demineralized water was used.

Three kinds of concrete mixes were realized:

- group A: reference concrete made using the 0.917 Na_2O eq. CPA cement and stored at 40°C and 100% RH.

- group B: concrete made with a 1.5% Na_2O eq. cement (addition of NaOH to the water) stored at 40°C and 100% RH.

- group C: concrete made with a 1.5% Na_2O eq. cement (addition of KOH to the water) stored at 40°C and 100% RH.

TABLE 1 - Chemical analysis of the cement used in this study (L.I. = Loss Ignition)

SiO_2	CaO	MgO	Na_2O	K_2O	Al_2O_3	Fe_2O_3	SO_3	L.I.	Total
16.20	69.75	1.98	0.26	1.08	4.73	2.62	2.54	1.00	100.16

Various sizes of concrete specimens were cast for each set of concrete mix (the position of the re-bars and the position of the extension gages are indicated in Fig. 1):
- 1 reinforced beam (15 x 25 x 230 cm; number 1 in Fig. 1).
- 1 prism (14 x 14 x 56 cm; number 2 in Fig. 1).
- 3 cylinders (16 cm dia. x 32 cm)
- 3 bars (7 x 7 x 28 cm; number 3 in Fig. 1).

RESULTS

Expansions

The measurements were conducted weekly over a period of 1 year on the concrete bars and prisms (Table 2). The concrete bars (7 x 7 x 28 cm) show expansions ranging between 0.6 and 1 ‰ (Fig. 3). It is interesting to point out that the 14 x 14 x 56 cm concrete prisms show higher expansions, ranging between 1.5 and 4 ‰ (Fig. 4). Expansion is therefore positively correlated to the specimen size. Similar observations were made by Bakker (4) and Locher (5).

The concrete specimens, stored at 40°C and 100% RH, show higher expansions than a reference concrete stored at 20°C (not showed in this study). These observations agree with many previous studies enlighten the influence of temperature and humidity on AAR (e.g. Stark (6), Olafsson (7)). Moreover, it is to point out that the concrete specimens with added KOH show higher expansions in the first three months compared with the concretes with added NaOH. However, after 3 months the concretes with added NaOH show the highest expansions: a 15 % difference was recorded after one year. A 50 to 60 % difference exists between the reference concrete stored at 40°C and 100% RH and the concretes with added KOH or NaOH. This difference enlighten the importance of alkalies in the development of the AAR.

The strain values measured after one year on the reinforced beams are presented in Fig. 2. As noticed previously, the highest expansion values were recorded, after one year, for the concrete with added NaOH. These results show higher strain values in central part of the beam compared with the lower and upper parts. The strain is therefore highly restrained by the longitudinal re-bars.

Microscopic observations

All the samples were observed with the SEM after 1, 3, 6, and 12 months. The AAR gel analyses were made with the coupled EDXA. AAR gels were first observed in the concrete with added KOH after 3 months. These observations agree with the expansion results showing, after three months, a higher expansion of the concrete with added KOH compared to the concrete with added NaOH. AAR gels were observed in all the 6 and 12 months' old concretes. However, in the concrete with no addition of alkalis, only little amounts of gels were observed. Usually massive gels with a smooth glassy surface are observed (Fig. 7 and 8). The gels also present sometimes coarse surfaces (Fig. 5) with an almost textured, spongy like, surface (Fig. 5 and 6). These different types of gel are similar to those classically described by Regourd et al (8) and Regourd-Moranville (9).

AAR gel analyses (EDXA)

The gel chemical composition shows important variations of the SiO_2, CaO, Na_2O and K_2O contents: SiO_2 range between 14 and 67 %, CaO range between 19 and 80 %, Na_2O range between 0 and 3 % and K_2O range between 0 and 19 %. Most of the alkali content variations in the AAR gels are of course related to the added alkalis in the concrete (NaOH or KOH). The average compositions of the gels observed after 6 and 12 months are given in table 3. It is to point out that the alkali contents of the gels increase with time: 1 year old gels are richer in alkalis than 6 months' old gels. The points are plotted in a SiO_2 versus Na_2O or K_2O graph (Fig. 9). This graph shows that in the concrete with added KOH, the gels are richer in alkali compared with the gels in the concrete with added NaOH. Two reasons may be given to explain these variations: first, potassium enter more easily in the gel composition; second, the sodium content is underestimated by the EDXA technique.

TABLE 3 - Average chemical composition of the AAR gel observed after 6 and 12 months

Analyses	Na_2O	MgO	Al_2O_3	SiO_2	S	Cl	K_2O	CaO	FeO
Concrete with added NaOH									
Gel (6 months)	0.22	0.51	4.56	24.54	0.09	0.00	0.18	69.38	0.75
Gel (12 months)	0.69	0.10	2.83	36.90	0.01	0.01	0.35	59.01	0.21
Concrete with added KOH									
Gel (6 months)	0.36	0.21	2.32	31.39	0.00	0.04	1.40	64.03	0.26
Gel (12 months)	1.11	0.24	0.98	52.85	0.11	0.03	8.49	35.85	0.34

Compressive strengths, tensile strengths (bending test) and elasticity modulus

The compressive strengths, tensile strengths and elasticity modulus were measured after 1, 3, 6 and 12 months. The results are presented in Table 4 and in Fig. 10, 11 and 12. All the concrete specimens show an increasing compressive strength with time (Fig. 10). No decrease related to the recorded AAR expansions was measured, but the concretes showing the highest expansions show also the lowest compressive strengths. It is however to point out that the concrete mixes with added alkalis show an important compressive strength increase after 3 months followed by a decrease down to "normal" values (see the dashed lines in Fig. 10). Such variations of compressive strengths are usually considered as due to the addition of NaOH (and/or KOH ?) influencing the cement paste hydration (Shayan and Ivanusec (10)). The tensile strength measurements are presented in Fig. 11. An important increase of the reference concrete tensile strength and a less important increase for the two other concrete mixes, affected by AAR, were recorded. Once again, important variations were observed after three months. It is also possible to consider that the addition of alkali influences the cement paste hydration and therefore the concrete mechanical characteristics.

The elasticity modulus variations are more important: after 3 months, the concretes with added KOH and NaOH show 40 to 50 % lower elasticity modulus compared with the reference concrete (Fig. 12). This reference concrete presents a normal behavior, that is to say an increasing

TABLE 2 - Measured expansions on the 7x7x28 bars and 14x14x56 prisms

Age (weeks)	Standard concrete stored at 40 °C and 100% RH		Concrete + NaOH (1.5% Na2O eq.) stored at 40 °C and 100% RH		Concrete + KOH (1.5% Na2O eq.) stored at 40 °C and 100% RH	
	(7x7x28) (‰)	(14x14x56) (‰)	(7x7x28) (‰)	(14x14x56) (‰)	(7x7x28) (‰)	(14x14x56) (‰)
0	0,00	0,00	0,00	0,00	0,00	0,00
2	-	-	-0,01	-0,02	-0,04	-0,04
3	-0,06	-0,06	-0,02	-0,04	0,05	0,05
4	-0,03	-0,03	0,08	0,08	0,13	0,13
5	0,06	0,06	0,16	0,16	0,24	0,27
6	0,08	0,24	0,27	0,19	0,25	0,37
7	0,08	0,32	0,28	0,21	0,29	0,51
8	-	-	0,32	0,23	0,33	0,90
9	0,30	0,52	0,36	0,40	0,35	1,00
10	-	-	0,40	0,70	0,33	1,10
11	-	-	0,43	0,90	0,31	1,40
12	0,37	0,83	0,46	1,10	-	-
13	-	-	-	-	0,40	1,60
14	-	-	0,50	1,60	-	-
16	0,40	1,02	0,67	2,00	-	-
17	-	-	-	-	0,58	2,10
18	-	-	0,78	2,40	-	-
20	-	-	-	-	0,66	2,40
21	-	-	0,81	2,90	-	-
24	-	-	-	-	0,66	2,70
25	0,49	1,32	0,86	3,50	-	-
31	-	-	-	-	0,71	2,90
32	0,60	1,45	0,89	3,67	-	-
53	0,70	1,60	0,92	3,92	0,81	3,31

TABLE 4 - Compressive strengths, tensile strengths and elastic modulus measured after 1, 3, 6 and 12 months

Age (months)	Standard concrete stored at 40°C and 100% RH			Concrete + NaOH stored at 40°C and 100% RH			Concrete + KOH stored at 40°C and 100% RH		
	C. S. (MPa)	T.S. (MPa)	E.M. (MPa)	C. S. (MPa)	T.S. (MPa)	E.M. (MPa)	C. S. (MPa)	T.S. (MPa)	E.M. (MPa)
1	45	2,85	0,032	35	3,11	0,028	35	2,71	0,030
3	50	3,01	0,029	54	2,15	0,021	52	1,98	0,023
6	55	3,40	0,032	42	2,94	0,015	47	3,11	0,019
12	55	4,33	0,034	42	3,21	0,017	47	3,26	0,020

C.S. = Compressive strength on 16x32 cylindric cores
T.S. = Tensile strength (bending test) on 7x7x28 bars
E.M. = Elastic modulus on 16x32 cylindric cores

Young modulus with time. Therefore, as noted by Hobbs (11, 12) and Swamy and Al-Asali (13), it seems that the elasticity modulus is more affected by the AAR than the compressive strength.

DISCUSSION AND CONCLUSIONS

This study shows, on the chemical point of view, that some variations of the gel composition are related to its age: the alkali contents of the AAR gels increase with time. AAR gels are known to present highly variable chemical compositions that are not very well understood. This study shows that some chemical variations, within the same sample, may be related to gel formed at different times. The gels are usually interpreted as more expansive with the increasing alkali content (Wang and Gillott (14)): therefore if the alkali content is increasing with time, the oldest gel will be also the most able to produce degradations.

This study shows, on the mechanical point of view, first, that the amount of AAR expansion is positively correlated with the specimen size. This observation, already made by several authors ((4), (5)), explain with AAR related degradations are more severe on big concrete structures like dams. Second, little or no variations of the concrete compressive strengths and tensile strengths were recorded. Third, an important decrease of the Young elasticity modulus (40 to 50 % loss) was observed. This loss is likely to have important consequences on the structural behavior of a concrete structure. These results will allow in the future to develop security factors evolutions based, for example, on a Finite Element detailed study of a concrete infrastructure (Diab and Prin (15)).

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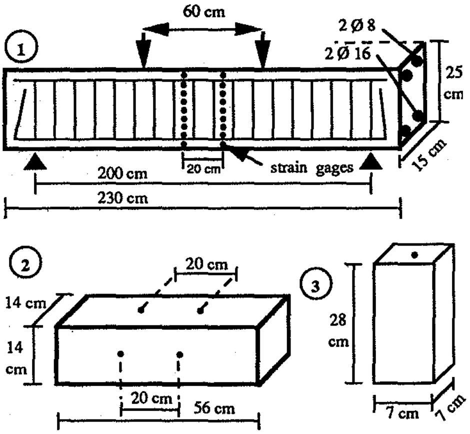

Figure 1 Description of the different types of concrete beams, prisms and bars

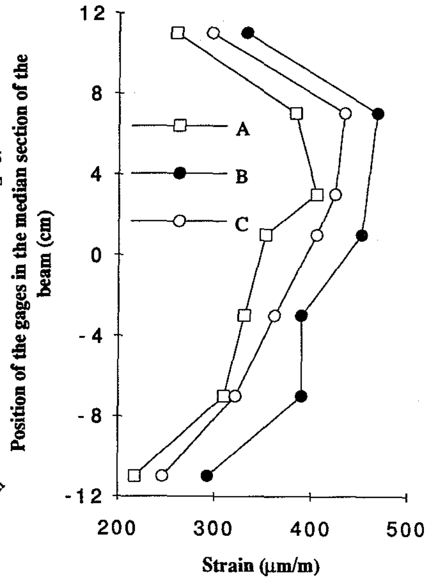

Figure 2 Strain values measured on the reinforced concrete beams after 1 year

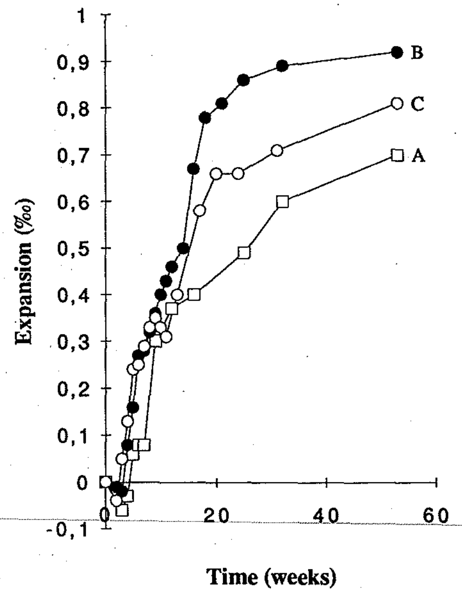

Figure 3 Measured expansions on the concrete bars (7 x 7 x 28)

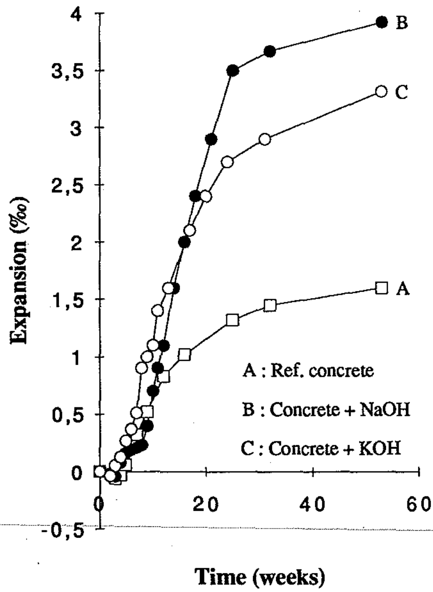

Figure 4 Measured expansions on the concrete prisms (14 x 14 x 56)

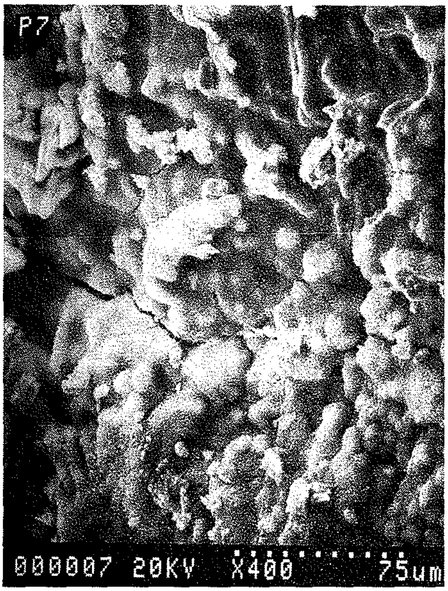

Figure 5 SEM micrograph of a massive gel (concrete + NaOH: 6 months)

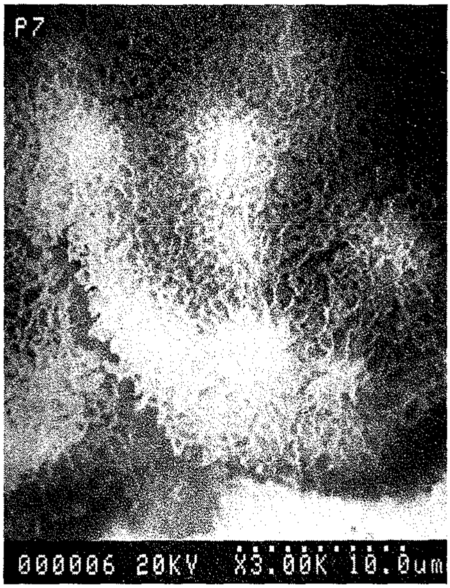

Figure 6 SEM micrograph of a gel with a spongy-like surface (zoom of Fig. 5)

Figure 7 SEM micrograph of a massive gel (concrete + KOH: 6 months)

Figure 8 SEM micrograph of a massive gel (concrete + NaOH: 12 months)

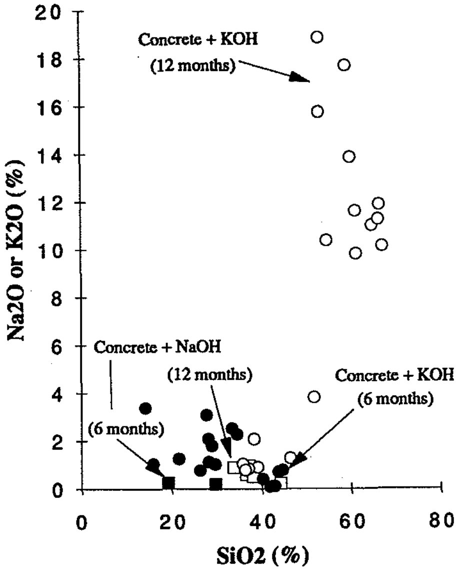

Figure 9 SiO_2 vs Na_2O or K_2O in the AAR gels (conc. + NaOH or + KOH after 6 & 12 months)

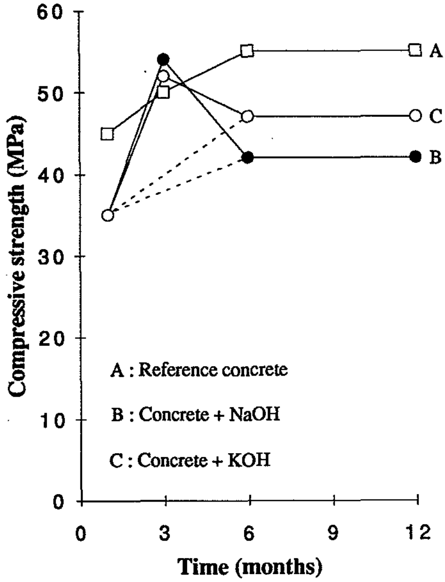

Figure 10 Variation of the concrete compressive strength with time

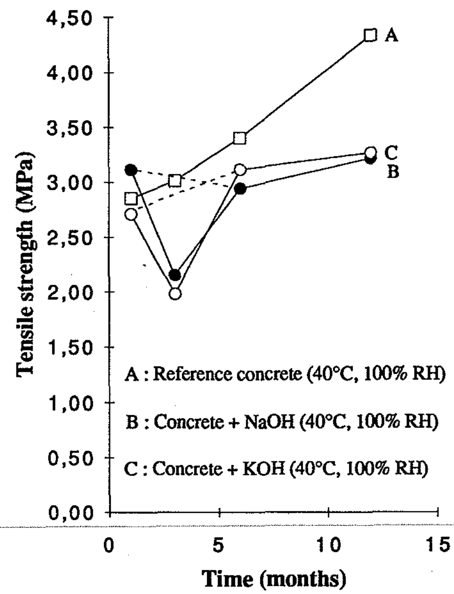

Figure 11 Variation of the concrete tensile strength with time

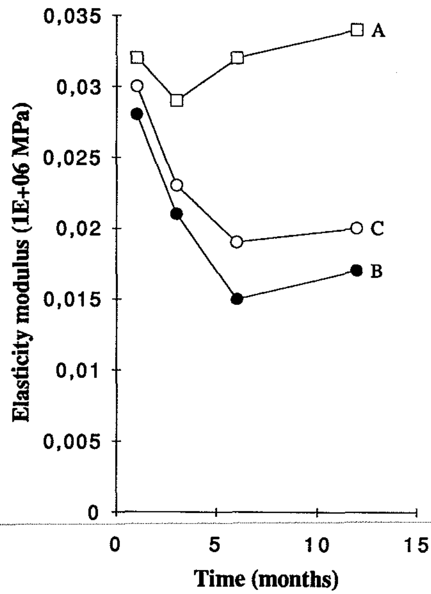

Figure 12 Variation of the concrete Young modulus with time