

# Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures

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#### Optimizing an expansion test for the 1 alkali silica of reaction in assessment 2 concrete structures 3

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#### 15 Abstract

16 This work is part of an overall project for the reassessment of concrete structures damaged by 17 ASR. The paper focuses on developing a laboratory method for expansion tests since the usual 18 tests appear to be difficult to use in expert assessment. The development involves optimizing the 19 storage conditions and the sizes of the specimen and aggregate. A combined effect of the 20 aggregate and specimen sizes on ASR expansion is thus pointed out: for a given mortar, the 21 expansion is lower in small specimens than in large specimens. Therefore, the ratio 'specimen size 22 / aggregate size' has to be sufficiently high to decrease this scale effect and obtain relevant 23 measurements. The discussion proposes a method for always using comparable conditions during 24 the expansion tests and finally suggests how this test can be optimized to provide fast and relevant 25 results for use in structure reassessment.

26 **Key Words**: alkali-silica reaction (ASR), expansion test, aggregate size, 27

- specimen size, scale effect
- 28 29
- 30

## 1 1. Introduction

Although several decades have passed since the first observations of ASR in concrete, safety of the ASR-damaged structures is still a subject of concern for owners. ASR involves the production of gels leading to an expansion of the concrete. It directly affects the behaviour of the structure such as power dams. However, other effects of ASR (e.g. cracking) should not be neglected, since it can lead to secondary effects (e.g. steel corrosion, freezing and thawing damages) which may be as important for the structure as the expansion achieved.

9 In this work, particular attention is paid to the assessment of future expansion of 10 the concrete in structures such as dams. It will determine whether it is possible to 11 continue to use these structures with or without repair and will help in structural 12 management. The most usual test is the residual expansion test at 38°C in air at 13 95% RH, which is performed on cores drilled from damaged structures [1-5]. 14 However, several criticisms can be made of this usual laboratory test: (1) the 15 reactive silica in the core of the aggregates is never reached in a short time 16 because of the large size of the aggregates used in structures (the asymptotic expansion is not achieved after one year of measurement) [6], (2) the ASR-gels do 17 18 not have the same composition in accelerated tests as in real structures because of 19 the impact of temperature on chemical equilibrium [7] and the substitution 20 process between alkalis and calcium [8-10], (3) alkali leaching during the tests 21 can have a deleterious effect on the assessment of the asymptotic expansion [11-22 14], (4) the high moisture conditions (higher than 95% RH) are difficult to 23 control, which leads to significant variations of ASR expansions for RH ranging 24 between 95 and 100% [15]. It therefore seems unrealistic to use the ASR-25 expansions obtained on cores in accelerated conditions to assess the future 2

expansion of concrete in the damaged structures. This view has been proved
 correct in the structural analysis of a French dam (small residual expansion in
 accelerated laboratory test and significant expansion measured on the dam) [6].

4 Therefore, a method has been proposed to obtain reliable experimental 5 information and avoid the uncertainty due to imperfect conditions of control in 6 laboratory tests [6]. In this method, the future ASR expansions are determined 7 through a finite elements analysis of the structures using two experimental data:

8 1) measurements performed directly on the structures to determine the9 amplitude of ASR expansion,

2) laboratory expansion tests on aggregate extracted from the structures toassess the expansion kinetics.

12 The laboratory tests are necessary to determine how the reaction advances13 according to the size of the aggregate [6].

14 The aim of this paper is to optimize the expansion test in terms of conditions of 15 storage, size of specimens and size of aggregates. Several experimental conditions 16 were assessed in order to rapidly evaluate the totality of the residual reactive 17 silica. The storage of the specimens should guarantee that all the residual reactive 18 silica is consumed in a short period of time. Tests were carried out in NaOH 19 solutions so that there was enough alkali to consume all the reactive silica, and at 20 60°C to accelerate the reaction. Alkalis had to reach all the reactive silica quickly. 21 Therefore, the specimens and the aggregates could not be too large in order to 22 decrease the time for alkalis to diffuse in the specimens and in the whole 23 aggregate. Finally, the tests were performed on several types of rocks to verify 24 whether they could differentiate between the reactivity of different aggregates.

## 1 2. Background

In order to use the results of expansion tests performed on specimens damaged by ASR for structure requalification, it is necessary to understand the effect of the size of the aggregate [16-31] and the size of the specimens [32-34] on the measured expansion. With this in mind, the development of ASR expansion can be described in several steps:

7 1. Alkalis present in the cement paste reach and diffuse into the aggregates8 (Figure 1-a).

9 2. Alkalis react with reactive silica and create ASR gel in and/or around the 10 aggregate. The gel can fill the connected porous volume surrounding the 11 aggregate in a thickness *t<sub>c</sub>* without leading to damage [35-37] (Figure 1-b). 12 3. Once the connected porosity is filled, the pressure in the gels increases and 13 causes cracking of the aggregate and the cement paste surrounding the 14 aggregate [37]. The propagation of cracks in specimens with large 'size of 15 the aggregate' to 'size of the specimen' ratios is rapid and can occur for 16 low pressures whereas it is more difficult for larger specimens and needs 17 higher pressure (Figure 1-c). This scale effect can be justified by fracture 18 mechanics concepts [38, 39]. Indeed, in the framework of the fracture 19 mechanics, the maximal normal stress in the vicinity of an inclusion (e.g. 20 aggregate), which induces a pressure on the cement matrix, is given by:

$$\sigma(r) = \frac{K_I}{\sqrt{2\pi r}} \tag{1}$$

21 where  $\sigma$  is the maximal normal stress at the point M located at *r*, the distance from 22 the edge of the inclusion (Figure 1-c) and  $K_I$  is the stress intensity factor obtained 23 from the relation:

$$K_I = p_g \cdot f\left(\frac{R_a}{L}\right) \tag{2}$$

1 where *f* is a function increasing with the ratio  $R_a/L$ , with  $R_a$ , the radius of the 2 aggregate and with *L*, the dimension of the specimen, and  $p_g$ , the gel pressure 3 which can be assessed from [37, 40]:

$$p_{g} = M_{g} \left\langle \frac{4}{3} \pi R_{a}^{3} s V_{gel}^{mol} - \varphi \frac{4}{3} \pi \left[ (R_{a} + t_{c})^{3} - R_{a}^{3} \right] \right\rangle$$
(3)

4 with  $M_g$  the gel elastic modulus, *s* the reactive silica content,  $V^{gel}_{mol}$  the molar 5 volume of the gel,  $\varphi$  the concrete porosity, and  $t_c$  the thickness along which the 6 gel can migrate from the aggregate to the cement paste.

Fracture mechanics concepts show that the greater the ratio 'size of the aggregate' to 'size of the specimen', the larger the normal stress at a given distance from the aggregate. Thus, the greater this ratio is, the smaller the pressure can be in the gel to reach the tensile stress at the boundary of the specimen (Figure 1-c).

4. Once cracks have reached the boundary of the specimens, ASR-gels can
leach off through the porosity induced by cracking and the pressure in the
gels falls, which stops the expansion (Figure 1-d). If the cracks reach the
boundary of the specimens at lower pressure, i.e. for experiments with
high 'size of the aggregate' to 'size of the specimen' ratio, lower
expansions can be measured, as observed in previous experimental works
[31-32].

An analysis of the background shows the importance of the concept of stress intensity factor in the understanding of the development of ASR expansion in concrete. The larger the stress intensity factor  $K_I$  is, the faster cracks appear and the cracking always leads to reduction of the expansion through gel permeation and exudation. Therefore, for several expansion tests, the stress intensity factor  $K_I$ has to be constant to maintain comparable mechanical conditions. The aim of this paper is first to optimize the expansion test but also to understand the effect of specimen size and aggregate size on expansion. Thus the study was performed on three sizes of specimens (20x20x160 mm, 40x40x160 mm and 70x70x280 mm) and four sizes of aggregates (0-315 µm, 315-630 µm, 630-1250 µm and 1250-2500 µm).

## 8 3. Experimental conditions

## 9 3.1 Materials

10 The cement used was a standard CEM I 52.5R (specific gravity: 3.1, surface area 11 (Blaine):  $400 \text{ m}^2/\text{kg}$ ). Its chemical composition is given in Table 1. Five 12 aggregates were used as crushed sands in the experiments: siliceous limestone 13 (SL), quartzite (Q), opal (O), quartz aggregate (QA) and marble (NR). Their 14 chemical compositions are given in Table 1. The first three aggregates are known 15 to be alkali-reactive and thus to develop ASR gels in a concrete environment. 16 They were chosen in different categories of rocks: sedimentary, metamorphic and 17 igneous. The reactive limestone (SL) contained mostly calcite and quartz, with 18 traces of dolomite, feldspars and phyllosilicates. Quartzite contained mainly 19 quartz with traces of muscovite and tridymite, opal contained principally quartz 20 and tridymite. The last two aggregates were considered as non-reactive. The non-21 reactive marble was almost exclusively composed of calcite. The aggregate in the 22 tests included four classes of reactive aggregates: C1 (0-315µm), C2 (315-23 630µm), C3 (630-1250µm) and C4 (1250-2500µm), and one class of non-reactive 24 aggregate  $(0-2500\mu m)$ .

### 1 **3.2 Sample preparation**

Mortars had a water/cement ratio of 0.5 and a sand  $(1512 \text{ kg/m}^3)$  / cement (504 kg/m<sup>3</sup>) ratio of 3. For the reference specimens, the sand was only composed of the non-reactive marble. For all the other specimens, the sand contained 30% of the aggregate under study and 70% of non-reactive marble. Mixtures were adjusted to fixed alkali contents (Na<sub>2</sub>O<sub>eq</sub>) by adding NaOH in the mixing water in order to have an alkali concentration in the pore solution close to the concentration in the storage solution (0.77, 1.0 and 1.25 mol/l).

#### 9 **3.3 Expansion measurements**

10 Deformation was measured on mortar prisms (20x20x160 mm, 40x40x160 mm 11 and 70x70x280 mm) using the scale micrometer method (specimens had 12 shrinkage bolts in the two extremities). Each length change value was the mean of 13 three values from three replicate specimens. Expansion measurements were 14 performed after the prisms had cooled to 20°C (~12h) in the NaOH solution.

### 15 **3.4 Specimen storage**

#### 16 3.4.1 Procedure

After demoulding, the specimens were first kept in sealed bags at 20°C for 14 days. Then, they were immersed in NaOH solution for the 14 following days. The aim of this step was to obtain the same concentration of alkali in the pore solution as in the storage solution. It was also intended to decrease the non-ASR expansion due to water absorption. The expansions were measured during this period, and the same amplitudes were obtained for both reactive and reference specimens. Thus, it was deduced that the expansions of the reactive specimens in this period were due to water absorption, and they were therefore neglected in the following
 analyses. After this period, the temperature of the solutions was increased to
 60°C.

#### 4 3.4.2 Choice of the solution concentration

5 In order to test the effect of alkali concentration on ASR expansion, mortars 6 containing siliceous limestone were kept in three different concentrations: 0.77, 7 1.0 and 1.25 mol/l. The mortars contained 15% of the size class C2, 15% of the 8 size class C3 and 70% of the non-reactive aggregate. The solutions were changed 9 at about 250 days in order to verify if the alkali concentrations were still sufficient 10 to react with aggregate.

11 The curves of the reactive mortars showed high initial rates of swelling (Figure 2), 12 followed by a low rate of expansion up to a final asymptote. The final expansions 13 for the three concentrations 0.77, 1.0 and 1.25 mol/l were 0.70%, 0.65% and 14 0.60% respectively. The difference between two consecutive concentrations 15 appeared to be negligible considering that the standard deviation for the 16 specimens was in the range of 0~0.02%. Finally, no changes were observed in the 17 expansion rates at 250 days when the solutions had been changed (Figure 2). 18 Thus, the alkali concentrations could be considered to have little influence on 19 ASR expansions in our tests, and a NaOH concentration of 1 mol/l was chosen for 20 the following tests.

# 4. Combined effect of aggregate and specimen 2 sizes

#### 3 4.1 Mortar mixtures

4 In order to study the effect of the size of the specimens, three kinds of prisms 5 were used: 20x20x160 mm, 40x40x160 mm and 70x70x280 mm. The particle size 6 distributions were obtained by adding 30% of reactive aggregate of the four 7 different size classes:C1 (0-315 µm), C2 (315-630 µm), C3 (630-1250 µm), C4 8 (1250-2500  $\mu$ m) to 70% of a continuous size distribution (0–2500  $\mu$ m) of non-9 reactive aggregate, the particle size distributions were different for the five 10 mortars. A previous study on these kinds of mixtures [40] had shown that the 11 effect of the difference of particle size distributions on the porosity of mortars did 12 not appear to be significant. The reference prisms were made with 100% of non-13 reactive aggregate. During the experiments, all mortar prisms were stored at 60°C 14 in the 1 mol/l NaOH solution.

#### 15 **4.2 Experimental results**

16 In order to assess mass variations and expansions only due to ASR, net values 17 were calculated and used in the following parts of the study. They were obtained 18 by subtracting the measurements of reference mortars (without reactive aggregate) 19 from those obtained on the reactive specimens. Figures 3, 4 and 5 present the 20 mass variations and the ASR expansions obtained on 20x20x160 mm, 21 40x40x160 mm and 70x70x280 mm specimens, respectively. All the curves show 22 a high and increasing initial rate of mass and swelling with time, followed by a 23 decrease of the rate until a long-term asymptote is reached.

1 In addition to the expansion measurement, the cracking patterns were observed 2 and the crack widths were measured at 290 days with a video-microscope (Figure 3 6). Crack widths were assessed on 15 points taken in at least 15 regions of the 4 specimens in order to obtain relevant average values. No cracking was observed 5 for the reference prisms and for the prisms containing the particles of size C1 6  $(0~315\mu m)$ , which is in accordance with the small expansion. For the other 7 specimens, the crack widths are given in Table 2. The largest specimens 8 (70x70x280 mm) presented the widest cracks (Figure 6 and Table 2). The smallest 9 prisms (20x20x160 mm) had the smallest cracks (Figure 6 and Table 2), which 10 were below the measurement limit of the video-microscope (<  $10 \,\mu$ m). The 11 differences between crack widths of mortars containing different aggregate sizes 12 were not significant (Table 2).

## 13 **4.3 Effect of specimen size**

14 Analysis of the ASR expansions demonstrated the significant effect of the size of 15 specimens. First, the largest specimens showed the slowest rate of ASR-expansion 16 whatever the aggregate size (Figure 7). This can be explained by the diffusion of 17 the alkalis into the specimens. The initial alkali concentration in the pore solution 18 was sufficient to initiate the reaction. Alkalis were quickly consumed by the ASR 19 gel and supplementary alkalis were necessary to maintain gel production. These 20 alkalis came from the solution and diffused into the mortar. Thus, they needed 21 longer to reach the centre of the largest specimens than the small ones.

The second effect was on the amplitude of the asymptotic ASR expansion, where
the largest specimens showed the highest asymptotic ASR expansion (Figure 7).
This was particularly significant on the large aggregate class 1250-2500 µm (ASR
expansions were twice as large for the 70 mm size specimens as for the others).

This observation shows the significant coupling effect between specimen size and
 aggregate size and confirms the anticipations explained in the 'background'
 section.

For the same size of aggregate, the proportion of aggregate particles close to the surface of the prism compared to the total aggregate increases with decreasing cross section of the prism. The gel created by the aggregate particles close to the surface of the prism is lost more easily than for the inner particles. In consequence, for the same size of aggregate, the smaller the specimen, the more significant the amount of gel lost by the cracks. This would explain the lower expansion measured (Figure 7).

11 In order to quantify the combined effect of the aggregate and the specimen size, 12 the ASR-expansion versus the ratio of the specimen size to reactive aggregate size 13 is plotted in Figure 8. For small aggregates (circled in Figure 8), the ASR-14 expansions were small due to the effect of the connected porous volume as 15 explained in the 'background' section. For larger aggregates, the 'prism size / 16 particle size' ratio had an important effect on measured expansions even for ratios 17 greater than 100. For example, the 315-630 µm aggregates presented expansion 18 about 20% larger for the 70x70x280 mm specimens (ratio equal to 200) than for 19 the 40x40x160 mm ones (ratio equal to 100 – Figures 7-a and 8). Such ratios are 20 largely higher than usual values, typically between 5 to 10, taken to choose a 21 specimen size according to aggregate size for compressive strength for example. 22 Therefore, it appears to be impossible to break free of this scale effect when 23 performing expansion tests, which leads to part of the expansion being neglected 24 compared to structural conditions. It is thus necessary to take this fact into account 25 when analysing the expansion tests that can be carried out with the theoretical 26 development presented in the background.

## 1 4.4 Effect of aggregate size

2 The effect of the reactive aggregate size on the ASR expansion has already been 3 extensively studied. Research has shown that the ASR expansion increases as the 4 reactive particle size is reduced. It could be noted that contrary results were found 5 for ACR (alkali-carbonate reaction) [41], since the higher expansions were found 6 for the larger aggregates. The cases of ASR have been researched in the works of 7 Hobbs and Gutteridge [21], Zhang et al. [22] and Kuroda et al. [23], who obtained 8 maximum expansions for size classes of 150-300 µm (opal), 80-150 µm (quartz 9 glass) and 150-300 µm (andesite), respectively. However, when the experiments 10 are performed with particles smaller than a few tens of a  $\mu$ m, it has frequently 11 been shown that the expansion does not increase continuously with the reduction 12 of particle size. Some authors obtained insignificant expansion when the sizes of 13 the reactive particles were under 50 to 150  $\mu$ m [17, 24, 25]. Only a few exceptions 14 of very small particles led to significant ASR expansions, all involving opal 15 aggregates [16, 26, 27]. Other research works clearly show a pessimum effect for 16 particle size, but for particles much larger than 100 µm [16, 17, 28-30]. These 17 investigations were usually performed on specimens of the same size. The 18 originality of the study presented here is to have used three sizes of specimens 19 with the same aggregate classes.

For all the specimens, it can be observed that the prisms containing small reactive particles (0-315 µm) have the lowest expansion (lower than 0.15% - Figures 3 to 5). For the three other aggregate sizes, the ASR expansions are significant and higher than 0.5%. The difference of ASR expansions for the small aggregate can be explained by the effect of the connected porosity. For the smallest aggregates, more of the gel can migrate in this connected porosity than for larger aggregates

1 and thus little ASR gel is available to cause expansion [37, 40]. In other words, it 2 is easier for the texture to accommodate a large number of small expansion sites 3 than a small scattered number of larger sites. At 150 days, the ASR expansion 4 presents a pessimum effect whatever the specimen size (Figure 9-a), as already 5 observed during previous investigations. But, after 400 days, when asymptotic 6 expansions had been reached, the pessimum had totally disappeared for the largest 7 specimens (Figure 9-b). For the largest aggregates, part of the difference of 8 expansion can be explained by a delay in the ASR expansion due to the diffusion 9 of the alkali in the aggregate [40]. The results of measurement confirm that the 10 expansion rate was slower in the largest particles whatever the size of the 11 specimens (Figures 3 to 5). However, even when the asymptotic value was 12 reached, ASR expansion remained lower for the largest aggregates in the smallest 13 specimens (Figure 9-b). This result shows that the pessimum effect is not only due 14 to the diffusion of alkalis in the aggregate, meaning that it is not an intrinsic 15 phenomenon but could be due to a scale effect that depends on the 'specimen size 16 / aggregate size' ratio.

17 In addition, the pessimum effect of aggregate size appears to be related to the 18 expansion capacity of the mortars. Compared with a previous study [38] which 19 was performed on mortars kept in saturated atmosphere (R.H. > 95%), the present 20 study showed a pessimum effect moving towards smaller aggregate. The mortars 21 conserved in the alkali solution were more expansive than the specimens in 22 saturated atmosphere due to the presence of sufficient alkali. Thus, it can be 23 concluded that the more expansive the mortar is, the more significant is the scale 24 effect. This can be explained by equations 1 to 3. The mortar is very expansive, 25 which means that more gel is produced (i.e. the gel molar volume is higher), and 26 then the gel pressure is larger than for less expansive mortar (equation 3). The

1 cracks appear for a constant value of the stress factor  $K_I$ . In consequence, if the 2 pressure increases, the function *f* referred to  $R_a/L$  must become smaller to keep  $K_I$ 3 constant. This means that the ratio  $R_a/L$  decreases and explains why the pessimum 4 moves towards smaller aggregate.

## 5 5. Tests on aggregates of different types

6 The aim of this part was to study the expansion test on several types of aggregate
7 to verify how it could differentiate between the reactivity of different aggregates.

#### 8 **5.1 Mortar mixtures**

9 In previous investigations [38], the reactive aggregate of sizes 315-630  $\mu$ m and 10 630-1250  $\mu$ m showed the same expansion. Therefore, it was decided to use 11 aggregate of size 315-1250  $\mu$ m for these experiments. The mortars had the 12 following particle size distribution: 30% of 315-1250  $\mu$ m and 70% of the non-13 reactive marble of size 0-2500  $\mu$ m. The test aggregates included four types: 14 siliceous limestone, quartzite, opal and quartz. All the mortars were conserved in 15 a 1 mol/l NaOH solution at 60°C.

#### 16 **5.2 Results**

The ASR expansions obtained for these four aggregates are plotted in Figure 10. After a slight delay, the mortar containing opal appeared to be the most reactive, with rather fast expansion and an asymptotic value of about 1.35%. The expansion of the mortar containing siliceous limestone was also quite rapid, but the final expansion was less (about 0.6%). The mortar with quartzite aggregate presented a slow expansion rate at the beginning but reached a final value about 0.5%, which was quite close to that of the siliceous limestone. ASR expansion of the mortar

1 with quartz aggregate was about 0.14%, which was small compared to the other 2 three (10%~28%). These results are consistent with experimental feedback on 3 these aggregates. Opal is known to be very reactive and to present large expansion 4 if the amount of available alkali is sufficient, while the other two potentially 5 reactive aggregates (siliceous limestone & quartzite) are usually less reactive and 6 present similar ASR expansions. In fact, owing to the large pressure developed by 7 ASR gels, the specimens containing opal were greatly damaged and cracked 8 (crack width of about 425 µm - Figure 11). The analysis performed in the 9 'background' section suggests that a great proportion of the ASR gel should have 10 permeated through these large cracks and thus not contributed to the expansion. 11 This was due to the large amount of reactive silica contained in opal, which 12 induced high gel pressure (Equation 3) and thus a greater stress intensity factor 13 (Equation 2) for opal than for the siliceous limestone.

#### 6. Discussion 14

15 The previous observations show the difficulty of obtaining a fast but relevant 16 expansion test on specimens. In expert assessments, the owners of structures often 17 expect fast results. To this end, it is interesting to note that the time necessary to 18 reach the expansion asymptote (assumed here to be reached when the difference 19 between two consecutive measured expansions is lower than 0.015%) increases 20 with the specimen and the aggregates sizes (Table 3). This influence can be 21 explained by the the diffusion of ionic species into the specimen and the 22 aggregates. Thus, the shortest time necessary to achieve expansion is about 23 56 days (Table 3), obtained for the smallest specimens (20x20x160 mm) and for 24 aggregate class C2 (315-630µm). For larger aggregates and specimens, the time is 25 always longer than 100 days (Table 3). Moreover, it is always difficult to obtain

1 adequate amount of material from existing structures that are still in use. From 2 this point of view, too, working on small specimens is interesting. The most 3 relevant, fast and convenient tests should use small expansive particles (315-4  $630 \,\mu\text{m}$ ) and small specimens ( $20x20x160 \,\text{mm}$ ). But, in this condition, a part of 5 the expansion is neglected because of the combined effect of aggregate and 6 specimen size (expansions measured on 20x20x160 mm specimens are 30% lower 7 than expansions obtained on 70x70x280 mm specimens). Moreover, section 5 8 showed the effect of the aggregate type on cracking due to differences in reactive 9 silica content. This could influence the analysis of the measured expansions.

10 In order to use expansion tests in predictive calculations, it is necessary to clarify 11 all the phenomena and quantify all the parameters involved during expansion. In 12 particular, the scale effect, which could make the measurements vary wildly 13 according to expansion conditions (storage, reactive silica content), should be 14 carefully considered. The parameters of the scale effect on ASR expansions 15 measured on specimens are defined in equations 2 and 3 of the first part of the 16 paper. In order to decrease the influence of this scale effect on ASR expansion, 17 the stress intensity factor  $K_I$  (equation 2) should be the same for the different 18 expansion tests, which means that the constants D1 and D2 in equations (4) and 19 (5) should be fixed.

$$\frac{4}{3}\pi R_a^3 s V_{gel}^{mol} - \varphi \frac{4}{3}\pi \left[ (R_a + t_c)^3 - R_a^3 \right] = D_1$$
(4)

$$\frac{R_a}{L} = D_2 \tag{5}$$

20 Once  $D_1$  and  $D_2$  are fixed, the aggregate size can be calculated with equation 4. 21 The values of  $V_{mol}^{gel}$  and  $t_c$  can be taken from previous papers ( $V_{mol}^{gel}$  of about 1 20.10<sup>-6</sup> m<sup>3</sup>/mol and  $t_c$  of about 10 µm in [37] and [40]). Then the specimen size 2 can be obtained with equation 5.

3 For example, in the case of the expansion tests on siliceous limestone and opal aggregates, the reactive silica content was 3000 mol/m<sup>3</sup> for the siliceous limestone 4 5 and 23000 mol/m<sup>3</sup> for opal. For the mortars of siliceous limestone, the aggregate 6 class C2 (315-630 µm) and the specimen size 20x20x160 mm were chosen, thus 7  $D_1$  and  $D_2$  were equal to 2.E-12 m<sup>3</sup> and 0.012. In order to have the same stress 8 intensity factor for opal as for siliceous limestone, the aggregate size (the mean 9 diameter) obtained by equation 4 should be about 215 µm and the specimen size 10 should be about 10 mm. With such experimental conditions, the ASR-expansions 11 for these two aggregates could be compared with more reliability.

## 12 **7. Conclusions**

13 The main aim of this paper was to analyse the expansion test in terms of storage 14 conditions. size of specimens (20x20x160 mm, 40x40x160 mm and 15 70x70x280 mm), and size of aggregate (0-315 µm, 315-630 µm, 630-1250 µm 16 and  $1250-2500 \,\mu\text{m}$ ) in order to obtain fast and relevant expansions. This test is 17 part of an overall methodology using measurements performed directly on 18 structures, finite element calculations and laboratory expansion tests on aggregate 19 extracted from structures to assess the expansion kinetics. The tests are used to 20 assess the residual reactive silica in the aggregates of various sizes used in the 21 structure to determine the advancement of the reaction according to the size of the 22 aggregate and thus to assess the kinetics of future expansions [6].

23 The following conclusions can be drawn:

- The expansion tests in three concentrations of NaOH solution (0.77 mol/l,
  1 mol/l, 1.25 mol/l) showed that, in the condition of abundant alkalis, the
  expansion is not influenced by the alkali concentration.
- For the same size of aggregate, small prisms needed the shortest time to
  achieve final expansions. For the same size of specimen, small-sized
  aggregate took the shortest time to reach the final expansions. These
  results can be explained by the faster diffusion of ionic species into the
  porosity of small prisms and into the aggregate.
- A combined effect of the aggregate and specimen sizes on ASR
  expansions has been highlighed. It appears that, even with a 'specimen size / aggregate size' ratio higher than 100, the scale effect still exists. It
  can be explained by the proportion of ASR gels that permeate out of the specimens, causing a decrease of the gel pressure and thus reducing the induced expansion.
- The most relevant, fast and convenient tests should use small reactive particles (315-630 µm) and small specimens (20x20x160 mm). But in this condition, a part of the expansion is neglected because of the coupled effect of aggregate and specimen size. So the results should be analyzed through the concept of stress intensity factor in order to take all the parameters into account in the measured ASR expansions
- Even if the expansion measurements are used through a finite element analysis, the expansion tests should be performed in comparable conditions. Therefore, nonlinear effects due to connected porosity or cracking should be avoided or well enough understood to be taken into consideration. Under this consideration, a methodology which takes

account of this effect has been proposed (in 6. Discussion) to make
 relevant expansion test. The validity of the method should be evaluated in
 future experiments.

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	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	Na <sub>2</sub> O <sub>eq</sub>	SO <sub>3</sub>	LOI
Cement	20.1	5.6	2.0	62.5	3.1	0.2	0.9	0.8	3.2	1.7
Non-reactive marble	-	-	-	54.4	0.5	0.001	-	-	0.01	43.0
Siliceous	15.4	1.5	0.7	40.4	1.4	0.4	0.4	0.7	4.2	35.6
Quarzite	87.7	4.0	1.0	0.4	0.2	0.1	0.9	0.7	0.1	1.1
Opal	92.7		0.3	0.2	0.1	0.2	0.1	0.2	1.1	6.0
Quartz	92.2	3.7	1.1	0.1	0.1	-	0.01	0.01	0.2	0.6

Table1: Chemical compositions of cement and aggregate (% by mass)

#### Table2: Crack widths for various aggregate and specimen sizes $(\mu m)$

Spec. size	20x20x160 mm	40x40x160 mm	70x70x280 mm
Agg. size			
С1/0-315 µт	<10	<10	<10
C2 / 315-630 µm	<10	50	360
C3 / 630-1250 µm	<10	60	335
C4 / 1250-2500 µm	<10	55	300
Average	<10 µm	~ 55 µm	~ 335 µm

# 

Table 3: Time necessary to achieve expansion for various aggregate and specimen sizes (days)

	315-630µm	630-1250µm	1250-2500µm
20x20x160 mm	56	120	148
40x40x160 mm	134	148	302
70x70x280 mm	301	342	393

## 



Figure 1: Development of ASR-gels in four steps: a) Diffusion of alkali in aggregates, b) Filling of connected porosity by ASR-gels, c) Tensile stresses in the cement paste around aggregate compared to tensile strength, d) Permeation of ASR-gels through cracks and exudation on the external boundary



Figure 2: Expansions on specimens with 30% siliceous limestone (SL) and 70% non-reactive limestone (reference R-100% non-reactive limestone) kept in NaOH solutions of different concentrations (0.77, 1.0 and 1.25 mol/l)



Figure 3: Mass variation (a) and expansions (b) on prismatic specimens 20x20x160 mm with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)



Figure 4: Mass variation (a) and expansions (b) on prismatic specimens 40x40x160 mm with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)



Figure 5: Mass variation (a) and ASR expansions (b) on prismatic specimens 70x70x280 mm with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)



- Figure 6: Cracking patterns of specimens cast with siliceous limestone (a) 70x70x280 mm (b)
- 40x40x160 mm and (c) 20x20x160 mm

- 7



Figure 7: ASR expansions on prismatic specimens 20x20x160 mm (a), 40x40x160 mm (b) and 70x70x280 mm (c) with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)



Figure 8: ASR expansions according to the 'Prism size / Particle Size' ratio



Figure 9: ASR expansions according to the average particle size after 150 days (a) and 400 days

(b)



- - Figure 11: Cracking patterns of specimens cast with opal (20x20x160 mm)