

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

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► **To cite this version:**

Xiao Xiao Gao, Stéphane Multon, Martin Cyr, Alain Sellier. Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures*, Springer Verlag, 2011, 44 (9), pp.1641-1653. 10.1617/s11527-011-9724-y . hal-01724662

HAL Id: hal-01724662

<https://hal.insa-toulouse.fr/hal-01724662>

Submitted on 23 Mar 2018

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

4

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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*

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1 **1. Introduction**

2 Although several decades have passed since the first observations of ASR in
3 concrete, safety of the ASR-damaged structures is still a subject of concern for
4 owners. ASR involves the production of gels leading to an expansion of the
5 concrete. It directly affects the behaviour of the structure such as power dams.
6 However, other effects of ASR (e.g. cracking) should not be neglected, since it
7 can lead to secondary effects (e.g. steel corrosion, freezing and thawing damages)
8 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
17 expansion is not achieved after one year of measurement) [6], (2) the ASR-gels do
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

1 expansion of concrete in the damaged structures. This view has been proved
2 correct in the structural analysis of a French dam (small residual expansion in
3 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 the
9 amplitude of ASR expansion,
- 10 2) laboratory expansion tests on aggregate extracted from the structures to
11 assess the expansion kinetics.

12 The laboratory tests are necessary to determine how the reaction advances
13 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**

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

- 7 1. Alkalis present in the cement paste reach and diffuse into the aggregates
8 (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_c 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:

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

21 where σ 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:

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

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]:

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

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

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

11 4. Once cracks have reached the boundary of the specimens, ASR-gels can
 12 leach off through the porosity induced by cracking and the pressure in the
 13 gels falls, which stops the expansion (Figure 1-d). If the cracks reach the
 14 boundary of the specimens at lower pressure, i.e. for experiments with
 15 high ‘size of the aggregate’ to ‘size of the specimen’ ratio, lower
 16 expansions can be measured, as observed in previous experimental works
 17 [31-32].

18 An analysis of the background shows the importance of the concept of stress
 19 intensity factor in the understanding of the development of ASR expansion in
 20 concrete. The larger the stress intensity factor K_I is, the faster cracks appear and
 21 the cracking always leads to reduction of the expansion through gel permeation

1 and exudation. Therefore, for several expansion tests, the stress intensity factor K_I
2 has to be constant to maintain comparable mechanical conditions. The aim of this
3 paper is first to optimize the expansion test but also to understand the effect of
4 specimen size and aggregate size on expansion. Thus the study was performed on
5 three sizes of specimens (20x20x160 mm, 40x40x160 mm and 70x70x280 mm)
6 and four sizes of aggregates (0-315 μm , 315-630 μm , 630-1250 μm and 1250-
7 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 m^2/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 (0-315 μm), C2 (315-
23 630 μm), C3 (630-1250 μm) and C4 (1250-2500 μm), and one class of non-reactive
24 aggregate (0-2500 μm).

1 **3.2 Sample preparation**

2 Mortars had a water/cement ratio of 0.5 and a sand (1512 kg/m³) / cement (504
3 kg/m³) ratio of 3. For the reference specimens, the sand was only composed of the
4 non-reactive marble. For all the other specimens, the sand contained 30% of the
5 aggregate under study and 70% of non-reactive marble. Mixtures were adjusted to
6 fixed alkali contents (Na₂O_{eq}) by adding NaOH in the mixing water in order to
7 have an alkali concentration in the pore solution close to the concentration in the
8 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*

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

1 were due to water absorption, and they were therefore neglected in the following
2 analyses. After this period, the temperature of the solutions was increased to
3 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.

1 **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 μm) to 70% of a continuous size distribution (0–2500 μm) 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 μ 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 μ 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.

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

1 This observation shows the significant coupling effect between specimen size and
2 aggregate size and confirms the anticipations explained in the ‘background’
3 section.

4 For the same size of aggregate, the proportion of aggregate particles close to the
5 surface of the prism compared to the total aggregate increases with decreasing
6 cross section of the prism. The gel created by the aggregate particles close to the
7 surface of the prism is lost more easily than for the inner particles. In
8 consequence, for the same size of aggregate, the smaller the specimen, the more
9 significant the amount of gel lost by the cracks. This would explain the lower
10 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 μm , 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 μm [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.

20 For all the specimens, it can be observed that the prisms containing small reactive
21 particles (0-315 μm) have the lowest expansion (lower than 0.15% - Figures 3 to
22 5). For the three other aggregate sizes, the ASR expansions are significant and
23 higher than 0.5%. The difference of ASR expansions for the small aggregate can
24 be explained by the effect of the connected porosity. For the smallest aggregates,
25 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 μm and
10 630-1250 μm showed the same expansion. Therefore, it was decided to use
11 aggregate of size 315-1250 μm for these experiments. The mortars had the
12 following particle size distribution: 30% of 315-1250 μm and 70% of the non-
13 reactive marble of size 0-2500 μm . 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**

17 The ASR expansions obtained for these four aggregates are plotted in Figure 10.
18 After a slight delay, the mortar containing opal appeared to be the most reactive,
19 with rather fast expansion and an asymptotic value of about 1.35%. The expansion
20 of the mortar containing siliceous limestone was also quite rapid, but the final
21 expansion was less (about 0.6%). The mortar with quartzite aggregate presented a
22 slow expansion rate at the beginning but reached a final value about 0.5%, which
23 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.

14 **6. Discussion**

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 (315-630 μm). 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 μm) and small specimens (20x20x160 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 D_1 and D_2 in equations (4) and
 19 (5) should be fixed.

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

$$\frac{R_a}{L} = D_2 \quad (5)$$

20 Once D_1 and D_2 are fixed, the aggregate size can be calculated with equation 4.

21 The values of V_{gel}^{mol} and t_c can be taken from previous papers (V_{gel}^{mol} of about

1 $20 \cdot 10^{-6} \text{ m}^3/\text{mol}$ and t_c of about $10 \text{ }\mu\text{m}$ 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
4 aggregates, the reactive silica content was $3000 \text{ mol}/\text{m}^3$ for the siliceous limestone
5 and $23000 \text{ mol}/\text{m}^3$ for opal. For the mortars of siliceous limestone, the aggregate
6 class C2 ($315\text{-}630 \text{ }\mu\text{m}$) and the specimen size $20 \times 20 \times 160 \text{ mm}$ were chosen, thus
7 D_1 and D_2 were equal to $2 \cdot 10^{-12} \text{ m}^3$ 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 $215 \text{ }\mu\text{m}$ 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 ($20 \times 20 \times 160 \text{ mm}$, $40 \times 40 \times 160 \text{ mm}$ and
15 $70 \times 70 \times 280 \text{ mm}$), and size of aggregate ($0\text{-}315 \text{ }\mu\text{m}$, $315\text{-}630 \text{ }\mu\text{m}$, $630\text{-}1250 \text{ }\mu\text{m}$
16 and $1250\text{-}2500 \text{ }\mu\text{m}$) 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:

- 1 • The expansion tests in three concentrations of NaOH solution (0.77 mol/l,
2 1 mol/l, 1.25 mol/l) showed that, in the condition of abundant alkalis, the
3 expansion is not influenced by the alkali concentration.
- 4 • For the same size of aggregate, small prisms needed the shortest time to
5 achieve final expansions. For the same size of specimen, small-sized
6 aggregate took the shortest time to reach the final expansions. These
7 results can be explained by the faster diffusion of ionic species into the
8 porosity of small prisms and into the aggregate.
- 9 • A combined effect of the aggregate and specimen sizes on ASR
10 expansions has been highlighted. It appears that, even with a ‘specimen
11 size / aggregate size’ ratio higher than 100, the scale effect still exists. It
12 can be explained by the proportion of ASR gels that permeate out of the
13 specimens, causing a decrease of the gel pressure and thus reducing the
14 induced expansion.
- 15 • The most relevant, fast and convenient tests should use small reactive
16 particles (315-630 μm) and small specimens (20x20x160 mm). But in this
17 condition, a part of the expansion is neglected because of the coupled
18 effect of aggregate and specimen size. So the results should be analyzed
19 through the concept of stress intensity factor in order to take all the
20 parameters into account in the measured ASR expansions
- 21 • Even if the expansion measurements are used through a finite element
22 analysis, the expansion tests should be performed in comparable
23 conditions. Therefore, nonlinear effects due to connected porosity or
24 cracking should be avoided or well enough understood to be taken into
25 consideration. Under this consideration, a methodology which takes

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

4

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1

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

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Na ₂ O _{eq}	SO ₃	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 limestone	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

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5 Table2: Crack widths for various aggregate and specimen sizes (μm)

<i>Spec. size</i>	20x20x160 mm	40x40x160 mm	70x70x280 mm
<i>Agg. size</i>			
<i>C1/0-315 μm</i>	<10	<10	<10
<i>C2 / 315-630 μm</i>	<10	50	360
<i>C3 / 630-1250 μm</i>	<10	60	335
<i>C4 / 1250-2500 μm</i>	<10	55	300
<i>Average</i>	<10 μm	~ 55 μm	~ 335 μm

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

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

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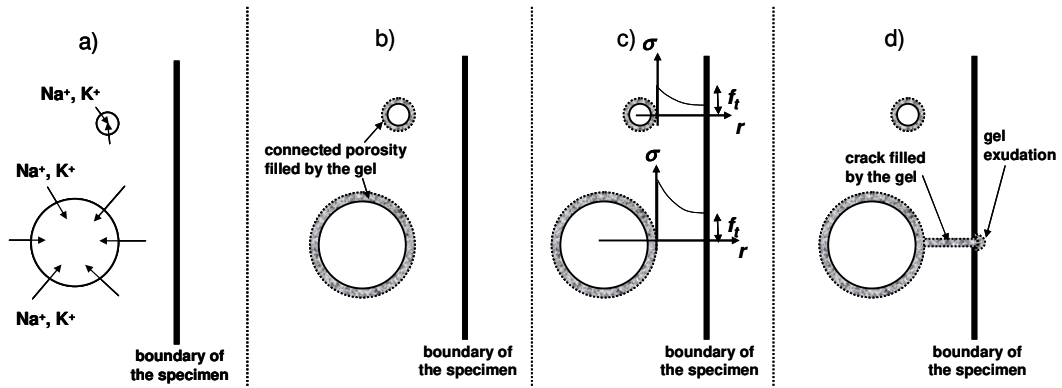


Figure 1: Development of ASR-gels in four steps: a) Diffusion of alkali in aggregates, b) Filling of connected porosity by ASR-gels, c) Tensile stresses in the cement paste around aggregate compared to tensile strength, d) Permeation of ASR-gels through cracks and exudation on the external boundary

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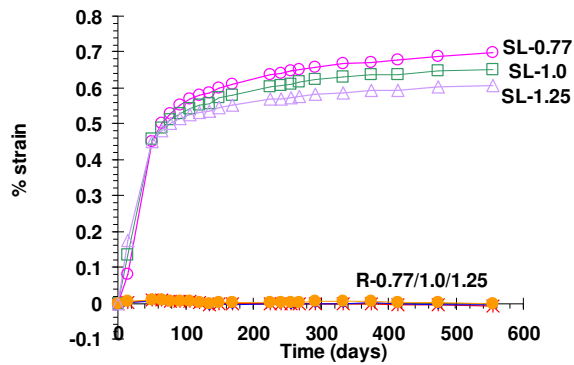
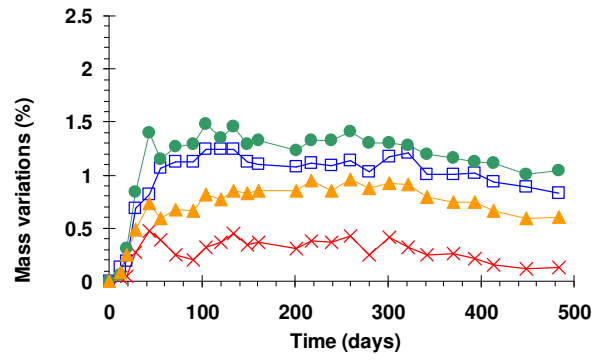


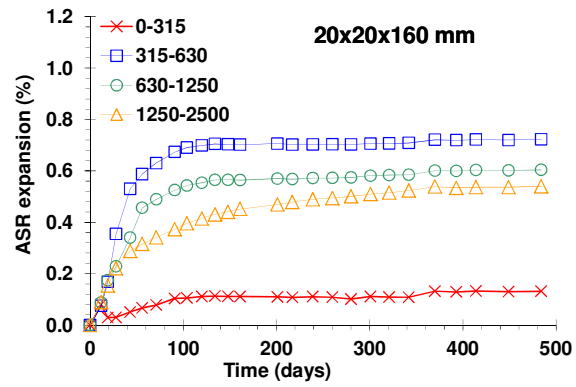
Figure 2: Expansions on specimens with 30% siliceous limestone (SL) and 70% non-reactive limestone (reference R-100% non-reactive limestone) kept in NaOH solutions of different concentrations (0.77, 1.0 and 1.25 mol/l)

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(a)



(b)

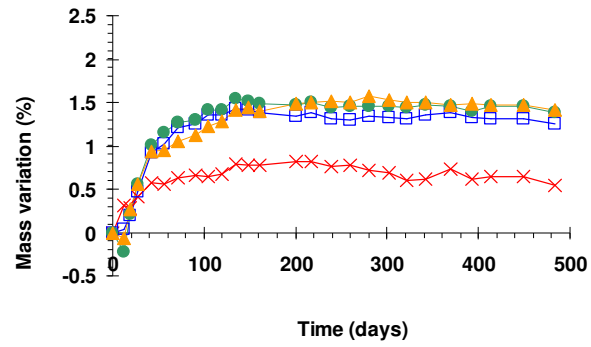
Figure 3: Mass variation (a) and expansions (b) on prismatic specimens 20x20x160 mm with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)

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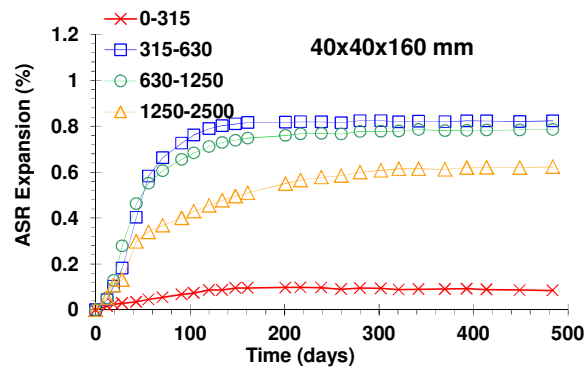
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(a)

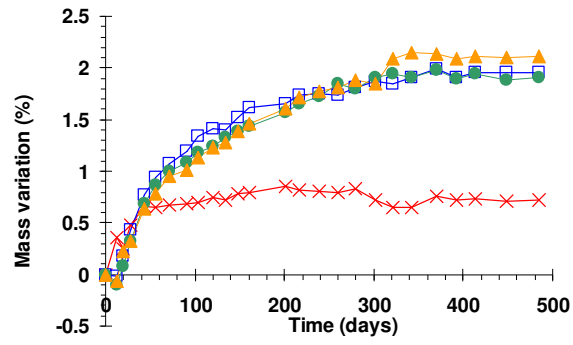


(b)

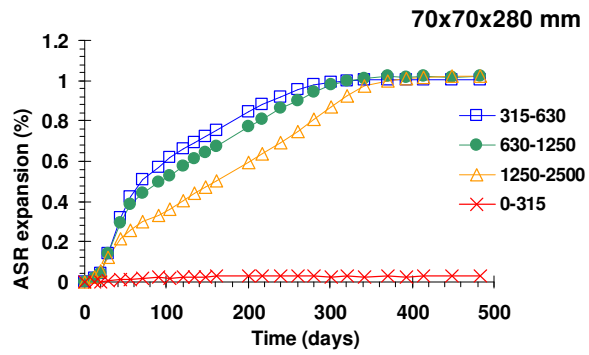
Figure 4: Mass variation (a) and expansions (b) on prismatic specimens 40x40x160 mm with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)

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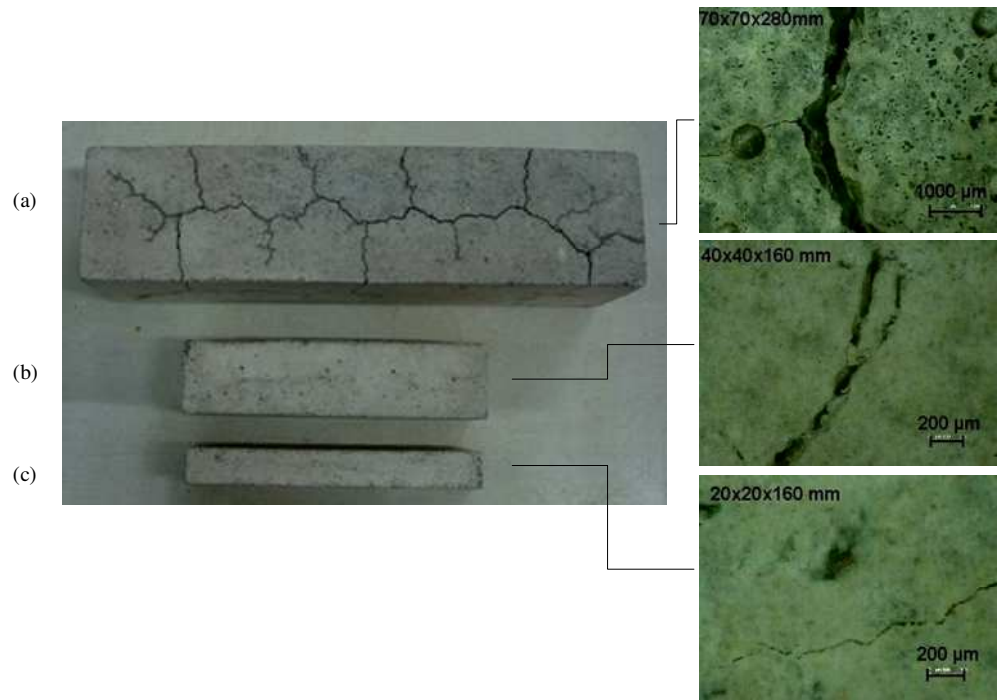
(a)



(b)

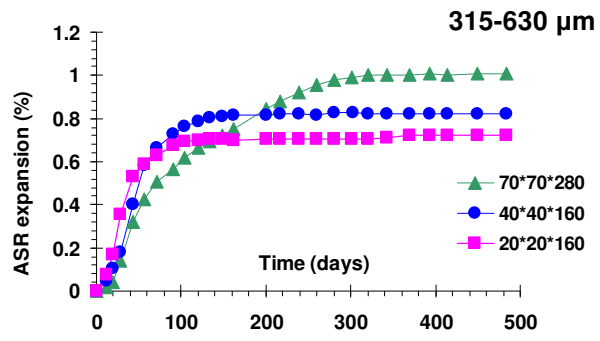
Figure 5: Mass variation (a) and ASR expansions (b) on prismatic specimens 70x70x280 mm with Siliceous Limestone (SL) aggregate kept in NaOH solution (1.0 mol/l)

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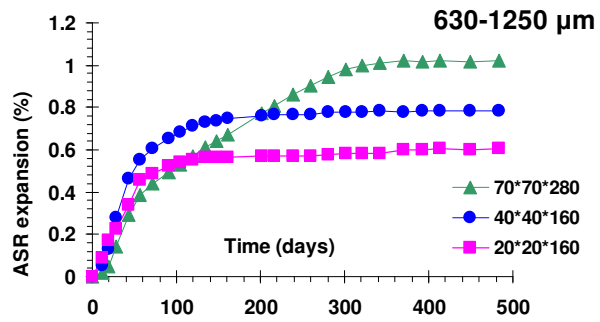


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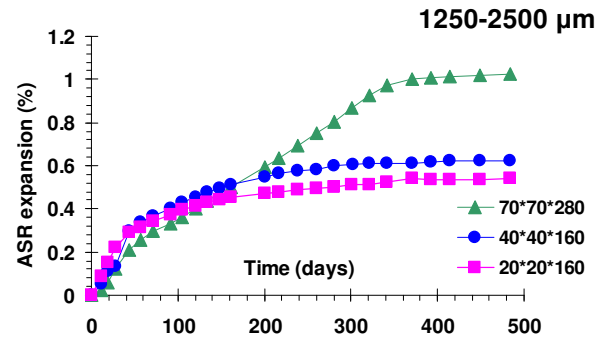
Figure 6: Cracking patterns of specimens cast with siliceous limestone (a) 70x70x280 mm (b) 40x40x160 mm and (c) 20x20x160 mm



(a)



(b)



(c)

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)

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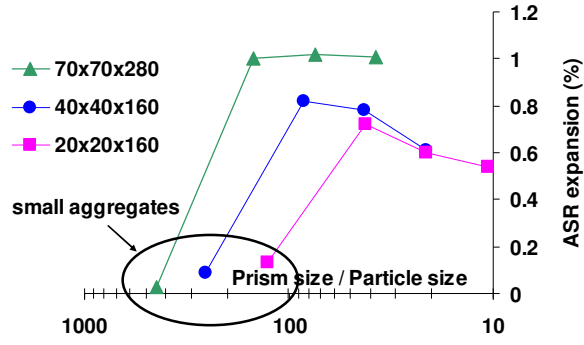
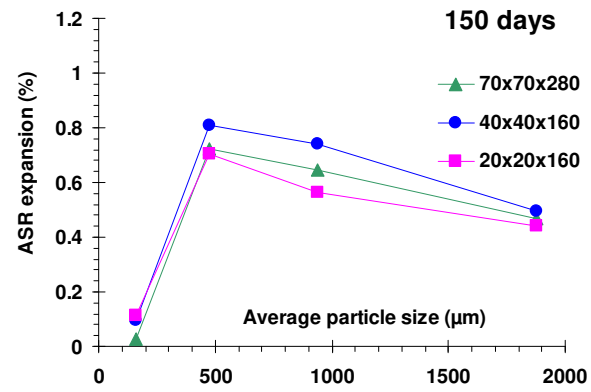
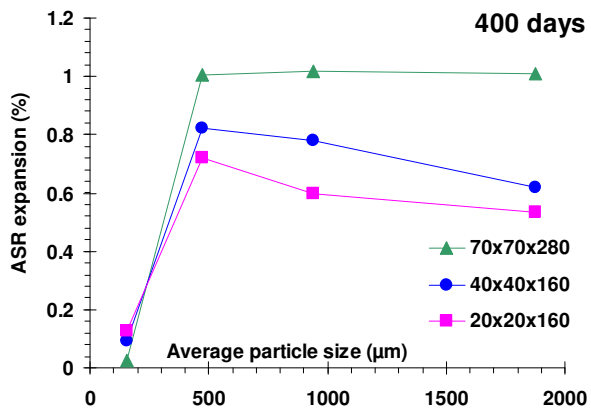


Figure 8: ASR expansions according to the 'Prism size / Particle Size' ratio

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(a)



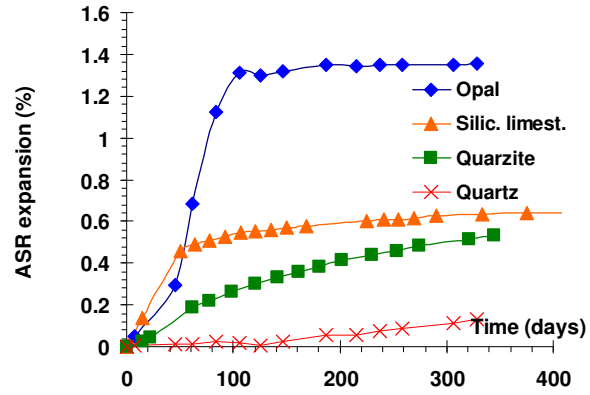
(b)

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

(b)

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3 Figure 10: ASR expansions according to the nature of the aggregate (reactive aggregate size: 315-
4 1250 μm , prism size: 20x20x160 mm)

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

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