



# Alkali–silica reaction (ASR) expansion: Pessimism effect versus scale effect

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## ABSTRACT

The effect of aggregate size on ASR expansions has been largely studied and conflicting results exist concerning the aggregate size that leads to the highest ASR expansion. Most of the research works clearly show a pessimism effect of aggregate size on ASR expansion. However, all the results available in the literature were obtained using different experimental conditions and the combined effects of other important parameters, such as specimen size used in the expansion tests, have often been neglected. This paper aims to investigate the combined effect of specimen size and aggregate size on ASR expansion. Experimental results highlight a scale effect, a combination of the effects of aggregate size and specimen size on ASR expansion. This scale effect appears to be influenced by the reactive silica content of the aggregate. Modelling at micro-scale level is used to propose a quantification of this effect.

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## 1. Introduction

Alkali–silica reaction (ASR) is a deleterious chemical reaction occurring in all types of structures that contain alkali-reactive aggregates: dams, bridges, roads, breakwaters, etc. The mechanism of expansion can be described in three main steps [1–4]: the diffusion of ionic species ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{OH}^-$ ,  $\text{Ca}^{2+}$ ) into the aggregates, the disruption of the silanol and siloxane bonds contained in the reactive silicate, and the reaction of alkali silicate with ionic species ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ) to form ASR gels. ASR gel induces pressure in the aggregate and in the cement paste, leading to stresses and thus cracking. ASR expansion depends on numerous parameters (amounts of alkali, reactive silica and water present, aggregate and specimen sizes, etc.).

It seems that the range of aggregate size causing the highest ASR expansion varies with the nature and composition of the aggregate. Numerous papers [5–23] discuss the effect on ASR expansion of particle sizes of reactive aggregates like opal [5–12], various kinds of silica glass, fused silica and waste silica glass, and so on [13–24]. Some research has shown that the expansion induced by ASR increases as the reactive particle size is reduced [9,14,17,19]. Some authors obtained insignificant expansion when the sizes of the reactive particles were under 50–150  $\mu\text{m}$  [11,13,15,22]. Furthermore, the use of powder from reactive aggregates like pozzolans, with particle sizes up to about 100  $\mu\text{m}$ , has been developed to counteract the effect of ASR [15,18,21]. Only a few exceptions with very small particles led to significant ASR expansions, all involving opal aggregates [5–7,12]. Other research works have shown a pessimism effect for various types of aggregates, with pessimism values occurring in a wide interval of particle sizes [4,7,8,10–13,16,20,23,24]. It is observed that, in

some cases, the most damaging size, leading to the highest ASR expansion, reaches more than 1 mm. The effect of “specimen size” has been much less studied [25–28]. Experiments performed with different ‘aggregate size to specimen size’ ratios show the effect of the size of the specimens on the ASR expansions measured. Lower expansions were measured on the smaller specimens [25,26].

First, a literature review showed that conflicting results exist concerning the most damaging reactive aggregate size, which leads to the highest ASR expansion. Secondly, experimentation performed by Zhang et al. [26] suggested that the two effects of aggregate and specimen sizes are combined. Therefore, the difficulty in generalizing results on the effect of the particle size of reactive aggregates could be explained by the differences in experimental conditions, and particularly the combined effects of aggregate size and specimen size on ASR expansion. This paper aims to investigate and quantify this scale effect and the influence the reactive silica content of aggregate has on the effect, in order to gain a better understanding of expansion tests.

The development of an ASR model at the microscopic level is a major concern of researchers trying to understand the mechanisms involved in the ASR and to predict future expansion. Previous modelling investigated the different aspects of the reaction: the mechanical consequences of ASR [29–32], the chemical mechanisms driving the attack of the aggregate by hydroxyl ions [33] and their coupling [34–38]. These works do not take into account the permeation of ASR gels in cracks which could be the main cause of the decrease of expansion by pessimism or scale effects. The concepts of fracture mechanics can explain the cracking phenomenon in the cases of aggregate in infinite matrix [39,40] or of central penny-shaped crack in sphere [41]. However, it is difficult to apply such models in the cases of specimens containing aggregates with numerous interactions (interactions with other neighbour aggregates and with specimen boundaries). The experiments presented in this paper were used to

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point out the dependence of expansion with aggregate and specimen sizes. These results are explained by fracture mechanics concepts. The teachings pointed out by fracture mechanics are then used to propose a simplified relationship to take into account the scale effect in an analytical modelling. Finally, the experimental results are used here to calibrate and discuss the validity and the capability of the model.

## 2. Experimental conditions and results

### 2.1. Experimental conditions

Expansion was measured on mortar prisms with a water/cement ratio of 0.5 and a sand ( $1512 \text{ kg/m}^3$ )/cement ( $504 \text{ kg/m}^3$ ) ratio of 3. Mixtures were adjusted by adding NaOH to the mixing water in order to have the same alkali concentration in the pore solution and in the storage solution. For the reference specimens, the sand was composed of the non-reactive marble only. For all the other specimens, the sand contained 30% of reactive aggregate and 70% of non-reactive marble. The prisms were stored in NaOH solution at  $60^\circ \text{C}$ . The expansion measurements were performed after the prisms had cooled to  $20^\circ \text{C}$  ( $\sim 12 \text{ h}$ ) in the NaOH solution. Each variation of length value was calculated as the mean of three values from three replicate specimens measured using the scale micrometer method (specimens had shrinkage bolts in the two extremities) [42,43]. The experimentation presented in this paper aimed to study three particular points.

#### 2.1.1. Effect of alkali concentration

As explained above, the specimens were kept immersed in NaOH solution. The aim of this part was to study three NaOH concentrations for immersion close to the standard conditions of  $1 \text{ mol/l}$  (0.77, 1 and  $1.25 \text{ mol/l}$ ). Reactive siliceous limestone was used to study the effect of alkali concentration on ASR expansion. The specimen and aggregate sizes were respectively  $20 \times 20 \times 160 \text{ mm}$  and  $315\text{--}1250 \mu\text{m}$  (15% of  $315\text{--}630$  and 15% of  $630\text{--}1250 \mu\text{m}$ ). Eighteen specimens (9 reactive and 9 reference specimens) were used for this part of the experimentation.

#### 2.1.2. Effect of reactive silica content

The second point concerned the effect of the reactive aggregate nature on ASR expansion. Four reactive aggregates with different reactive silica contents were chosen and tested. Opal (O) is known to be very reactive and to give large expansion if the amount of available alkali is sufficient. Quartzite (Q) and siliceous limestone (SL) are usually less reactive but can exhibit significant expansion in concrete. Quartz aggregate (QA), which contains mostly quartz, is considered as non-reactive. The silica contents of the aggregate [43] are given in Table 1. The aggregates were used to cast  $20 \times 20 \times 160 \text{ mm}$  specimens with  $315\text{--}1250 \mu\text{m}$  reactive aggregate (15% of  $315\text{--}630$  and 15% of  $630\text{--}1250 \mu\text{m}$ ). The 15 specimens were kept in  $1 \text{ mol/l}$  NaOH solution.

#### 2.1.3. Combined effect of aggregate and specimen sizes

Four reactive aggregate size classes: C1 ( $0\text{--}315 \mu\text{m}$ ), C2 ( $315\text{--}630 \mu\text{m}$ ), C3 ( $630\text{--}1250 \mu\text{m}$ ) and C4 ( $1250\text{--}2500 \mu\text{m}$ ) and three specimen sizes:  $20 \times 20 \times 160 \text{ mm}$ ,  $40 \times 40 \times 160 \text{ mm}$  and  $70 \times 70 \times 280 \text{ mm}$  were used to research the combined effect of aggregate and specimen

sizes on ASR expansion. The 45 specimens (36 reactive and 9 non-reactive specimens) were stored in  $1 \text{ mol/l}$  NaOH solution. Siliceous limestone was used as the reactive aggregate.

### 2.2. Experimental results

#### 2.2.1. Effect of the alkali concentration

The final expansions for the three NaOH concentrations of 0.77, 1.0 and  $1.25 \text{ mol/l}$  were 0.67%, 0.64% and 0.60% respectively (Fig. 1). The difference between two consecutive concentrations appeared to be small considering that the standard deviation for the specimens was in the range of 0–0.02%. Between 0.77 and  $1.25 \text{ mol/l}$ , the alkali concentrations could be considered to have little influence on ASR expansions in conditions of abundant alkali.

#### 2.2.2. Effect of the reactive silica content

The ASR expansions obtained for the four aggregates are plotted in Fig. 1. The specimens containing opal were the most reactive, with fast expansion and an asymptotic value of about 1.35%. The specimens with siliceous limestone exhibited rapid expansion, but the final expansions were lower (about 0.6%). The specimens with quartzite aggregate presented a slow expansion rate but reached a final expansion of about 0.55%. ASR expansion of the specimens containing quartz aggregate was about 0.14%. By the end of the experiment, the specimens containing opal were seriously damaged and cracked (crack width of about  $425 \mu\text{m}$ ) while the other specimens showed cracks with widths smaller than  $10 \mu\text{m}$  (Fig. 2). The reliability of measured expansions could have been affected by such cracking. However, the coefficient of variations obtained for three specimens was lower than 5%. It shows that the expansion scattering stayed quite small in spite of the large cracks.

#### 2.2.3. Combined effects of aggregate and specimen sizes

The ASR expansions obtained for mortars containing the reactive siliceous limestone with various aggregate sizes and cast in specimens of different sizes are given in Fig. 3. First, the specimens containing small reactive particles ( $0\text{--}315 \mu\text{m}$ ) had the smallest expansion (lower than 0.15%), confirming results found in the literature. The ASR expansions were significant and higher than 0.5% for the other three aggregate sizes. Concerning final ASR expansion, the largest specimens showed the highest ASR expansion (Fig. 4). This was particularly significant on the large aggregate class  $1250\text{--}2500 \mu\text{m}$  (ASR expansions were twice as large for the  $70 \times 70 \times 280\text{-mm}$  specimens as for the others). Moreover, ASR expansions presented a pessimum effect with the reactive aggregate

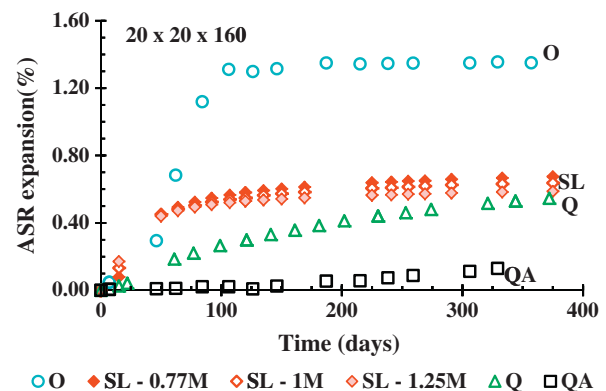


Fig. 1. ASR expansions according to the alkali concentration of the immersion solution for SL (0.77, 1.0 and  $1.25 \text{ mol/l}$ ) and to the nature of the aggregate (O: opal, SL: siliceous limestone, Q: quartzite and QA: quartz aggregate) stored in the  $1 \text{ mol/l}$  NaOH immersion solution.

Table 1  
Reactive silica contents of different aggregates [43].

Reactive silica ( $\text{SiO}_2$ )	SL	O	Q	QA
Percentage by mass (%)	6.9	50.4	7.6	2.7
Content ( $\text{mol/m}^3$ of aggregate)	3000	21900	3300	1170

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