

Effects of aggregate size and alkali content on ASR expansion

Stéphane Multon, Martin Cyr, Alain Sellier, Paco Diederich, Laurent Petit

► **To cite this version:**

Stéphane Multon, Martin Cyr, Alain Sellier, Paco Diederich, Laurent Petit. Effects of aggregate size and alkali content on ASR expansion. *Cement and Concrete Research*, Elsevier, 2010, 40 (4), pp.508–516. 10.1016/j.cemconres.2009.08.002 . hal-01724664

HAL Id: hal-01724664

<https://hal.insa-toulouse.fr/hal-01724664>

Submitted on 23 Mar 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 EFFECTS OF AGGREGATE SIZE AND ALKALI CONTENT ON ASR EXPANSION

2
3 Stéphane Multon^a, Martin Cyr^{a,*}, Alain Sellier^a, Paco Diederich^a, Laurent Petit^b

4
5 ^a Université de Toulouse; UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des
6 Constructions); 135, avenue de Rangueil; F-31 077 TOULOUSE cedex 4, France.

7 ^b Electricité de France (EDF) - Recherche et Développement, Avenue des Renardières, 77818
8 MORET SUR LOING Cedex, France

9 10 ABSTRACT

11 Attempts to model ASR expansion are usually limited by the difficulty of taking into account
12 the heterogeneous nature and size range of reactive aggregates. This work is a part of an
13 overall project aimed at developing models to predict the potential expansion of concrete
14 containing alkali-reactive aggregates. The paper gives measurements in order to provide
15 experimental data concerning the effect of particle size of an alkali-reactive siliceous
16 limestone on mortar expansion. Results show that no expansion was measured on the mortars
17 using small particles (under 80 μm) while the coarse particles (0.63-1.25 mm) gave the largest
18 expansions (0.33%). When two sizes of aggregate were used, ASR-expansions decreased with
19 the proportion of small particles. Models are proposed to study correlations between the
20 measured expansions and parameters such as the size of aggregates and the alkali and reactive
21 silica contents. The pessimum effect of reactive aggregate size is assessed and the
22 consequences on accelerated laboratory tests are discussed.

23
24 **Keywords:** Particle Size Distribution (B), Alkali-Aggregate Reaction (C), Alkalis (D),
25 Modeling (E), pessimum of aggregate size

26 27 28 1 INTRODUCTION

29 Reassessment of structures (bridges and dams) damaged by the Alkali-Silica-Reaction is of
30 prime importance for engineering structure owners. The gel volume formed by the chemical
31 reaction can be used as input data to structural models [1]. One of the main difficulties is to
32 assess the volume of this gel [2]. Microscopic models [3-7] could be one method of doing
33 this. Such models should be able to predict the differences of expansions with the variation of
34 all influential parameters (size of aggregate, silica content, alkali content, etc.) and have to be
35 compared with experimental results.

* Correspondence to: cyr@insa-toulouse.fr

36 Numerous papers deal with the effect of particle size of reactive aggregates on the expansion
37 due to ASR. Experiments have been performed on several types of aggregates. It seems that
38 which aggregate size causes the highest ASR expansion depends on the nature and
39 composition of the aggregate. Significant differences have been observed between rapid and
40 slow alkali-reactive aggregates. Opal was one of the earliest and most widely used aggregates
41 in laboratory studies of the size effect [8-12]. Investigations on the size effect have also been
42 performed with different kinds of silica glass, fused silica, waste silica glass, andesite,
43 siliceous limestone, quartzite, greywacke, chert, mylonite, flint and sandstone [13-18]. In
44 spite of all these studies, it is difficult to generalize about the effect of the particle size of
45 reactive aggregates, since conflicting results exist concerning the most damaging size that
46 leads to the highest ASR expansion. All the results available in the literature were obtained
47 using different experimental conditions and the effects due to coupling with other important
48 parameters, such as Na/Si ratio, have been often neglected.

49 A few papers deal with the effect of size for reactive siliceous limestone [6,8,9,19]. This type
50 of aggregate has been used in many damaged structures in France. Therefore, in order to test
51 models to predict the potential expansion of concrete containing such alkali-reactive
52 aggregates, tests have been performed to provide experimental data on the effect of particle
53 size of an alkali-reactive siliceous limestone on mortar expansion. This paper presents the
54 experimental results (expansion measurements performed over more than 500 days at 60°C)
55 and gives data necessary for model development.

56 Sixteen mix-designs were studied and special attention was paid to the proportions of alkalis
57 ($\text{Na}_2\text{O}_{\text{eq}}$) in the mixtures and reactive silica in the aggregate. First, the paper presents the
58 experimental conditions of the tests. Then, the measurements of ASR-expansions are
59 presented in two parts: experiments on mortars containing one reactive size distribution (0-
60 80 μm , 80-160 μm , 160-315 μm , 315-630 μm ; 630-1250 μm , or 1250-2500 μm) and
61 experiments on mortars containing mixes of two sizes of aggregate (0-80 μm and 1250-
62 3150 μm) with increasing 0-80 μm reactive aggregate content. Finally, models are proposed
63 to analyze the experimental results by studying correlations between the measured expansions
64 and parameters such as the size of aggregates and the alkali and reactive silica contents. A
65 time-dependent model allows the pessimum effect of reactive aggregate size to be assessed
66 and its consequences on accelerated laboratory tests are discussed at the end.

67

68 **2 EXPERIMENTAL CONDITIONS**

69 **2.1 Materials**

70 The cement used was a standard CEM I 52,5R with a specific gravity of 3.1 and a specific
71 surface area (Blaine) of 400 m²/kg. Its chemical composition is given in Table 1. The
72 aggregates were crushed sands (jaw crusher): a non-reactive marble (NR) and a reactive
73 siliceous limestone (R). The chemical composition of aggregates NR and R are given in Table
74 1. The non-reactive marble was mainly composed of calcite. The reactive siliceous limestone
75 contained mostly calcite and quartz, with traces of dolomite, feldspars and phyllosilicates. In
76 order to control the particle size distribution of the aggregates in the mortars, the aggregate
77 samples were divided into several particle size fractions: 0-80, 80-160, 160-315, 315-630,
78 630-1250, 1250-2500 and 1250-3150 μm). Details of the aggregate combinations are given in
79 2.3.

80
81 **2.2 Methods**

82 Expansion was measured on mortar prisms (2x2x16cm) with a sand (1512 kg/m³) to cement
83 (504 kg/m³) ratio of 3. The mortar prisms were demolded 24 hours after casting and were then
84 kept in sealed bags at 20°C until 28 days. At 28 days of age, the prisms were stored at 60°C,
85 after being placed on grids in watertight containers containing 20 mm of water (mortar bars
86 were not in contact with water). Salt (K₂SO₄) was added to the water (above saturation) in
87 order to maintain a relative humidity above 95% in the containers and to try to avoid
88 condensation on the specimens. Expansion was measured using the scale micrometer method
89 (specimens had shrinkage bolts at both ends). Each measurement was the mean of three
90 values from three replicate specimens. Expansion measurements were performed after the
91 containers and the prisms had been cooled for 24 hours at 20°C.

92 In order to reach specific Na/Si ratios, mixtures were adjusted to alkali contents (Na₂O_{eq}) of
93 6.2, 8.1 and 9.9 kg of alkali per m³ of mortar by adding NaOH in the mixing water. An alkali-
94 free superplasticizer was used (0.5% dry matter of cement mass) in mortars to achieve a
95 proper set in the molds.

96 For the first part, the water-cement ratio was 0.5. For the second part, the largest content
97 (40%) of fine reactive particles (0-80 μm) absorbed too much water during the casting, the
98 mortar was too dry to be cast with a ratio of 0.5 (even with a superplasticizer). Therefore, the
99 water-cement ratio was increased to 0.6.

100

101 **2.3 Experimental program**

102 2.3.1 Size effect

103 The first experimentation presented in this paper concerns the study of size effects of the
104 reactive siliceous limestone on ASR expansions. In this part, six particle size fractions were
105 studied in mortars: 0-80 (mortar M1), 80-160 (M2), 160-315 (M3), 315-630 (M4), 630-1250
106 (M5) and 1250-2500 μm (M6). These mortars contained 8.1 kg of alkali per m^3 of mortar. In
107 order to obtain significant expansions with the aggregate studied in this paper, the content of
108 reactive aggregate had to be at least 30%. The particle size distributions (Figure 1) were
109 obtained by adding 30% of reactive aggregate of the six different fractions to 70% of a
110 continuous size distribution (0-2500 mm) of non-reactive aggregate. Therefore, the particle
111 size distributions were different for the six mortars. The effect of such differences in particle
112 size distribution on the porosity of mortars was studied on mortars containing only non-
113 reactive particles. Porosities measured using the AFPC-AFREM method [20] laid between
114 17.3 and 18.2%. The differences did not appear to be significant compared to difference of
115 1% which could be obtained during measurements made on three specimens of a given
116 mortar.

117

118 2.3.2 Effect of fine reactive aggregate

119 For the second part of the experimentation, reactive particles of two sizes were used: 0-80 μm
120 and 1250-3150 μm , in mortars containing 6.2 and 9.9 kg of alkalis per m^3 of mortar.
121 Aggregates in all mortars had an equivalent particle size distribution and were composed of
122 40% of 0-80 μm particles, 30% of 315-630 μm particles and 30% of 1250-3150 μm particles.
123 For the five reactive mortar mixtures studied, all the 315-630 μm particles were non-reactive
124 and all the 1250-3150 μm particles were reactive. Only the nature of 0-80 μm particles
125 changed: mortars M7, M8, M9, M10 and M11 contained 0%, 10%, 20%, 30% and 40% of 0-
126 80 μm reactive aggregate and 40%, 30%, 20%, 10% and 0% of 0-80 μm non-reactive
127 aggregate, respectively. Therefore, mortars M7, M8, M9, M10 and M11 contained a total of
128 30%, 40%, 50%, 60% and 70% of reactive particles, respectively. Moreover, measurements
129 were performed on two reference mortars with only non-reactive aggregates (one for each
130 alkali content).

131

132 **3 EXPERIMENTAL RESULTS**

133 **3.1 Size effect**

134 The experimental results are presented in Figures 2 and 3. The ASR-expansions presented in
135 these figures were obtained by subtracting the expansion of the reference mortar (without
136 reactive aggregate) from the total expansion, as already proposed by some authors [21-23].
137 The long-term expansion of the reference mortars was 0.03%. The kinetics of the ASR-
138 expansions measured for 500 days are given in Figure 2. After 500 days of exposure at 60°C
139 and 95% R.H., mortars containing small reactive particles (0-80 and 80-160 μm) showed
140 ASR-expansions lower than about 0.01% (Figure 3). ASR-expansions were measured for all
141 the other mortars using particles larger than 160 μm : 0.057% for 160-315 μm reactive
142 particles, 0.315% for 315-630 μm particles, 0.328% for 630-1250 μm particles and 0.267%
143 for 1250-2500 μm particles.

144 **3.2 Effect of fine reactive aggregate**

145 Measurements of the ASR-expansions were taken for more than 500 days for the two alkali
146 contents (Figures 4 and 5). The ASR-expansions presented were obtained by subtracting the
147 expansion of the reference mortar from the total expansion. The long-term expansions of the
148 reference mortars were 0.02% and 0.03% for the low and the high alkali contents,
149 respectively. For the two alkali contents, the mortars containing only the large reactive
150 particles (M7) showed the largest ASR-expansions. Figure 6 shows the last ASR-expansion
151 measured, related to the amount of fine reactive particles in the mortar mixtures. ASR-
152 expansion decreased with the amount of fine reactive particles in the mortars: the more fine
153 reactive particles the mortar contained, the smaller was the ASR-expansion.

155 **4 MODEL AND DISCUSSION**

156 The models presented in this section aim to improve the understanding of the experimental
157 results obtained in the first part. The first model assesses the asymptotic expansion of mortars
158 containing only one size (first set of experiments) or the mixture of two sizes (second set of
159 experiments) of reactive aggregates. In order to integrate the dependence of swelling over
160 time, a second model is then proposed. It will be shown that for a given duration of test and a
161 given alkali content, the expansion is maximized for a specific range of aggregate size
162 (pessimum effect). However, the time-dependent model does not consider the mixture of
163 aggregates of different sizes for the moment. Finally, it should be noted that the fitted
164 parameters supplied here are only applicable for the aggregate studied in this paper.

166

167 4.1 Asymptotic expansion model

168 4.1.1 Effects of aggregate size and alkali content on asymptotic expansion

169 For this reactive limestone, no ASR expansion was measured for small reactive particles (less
170 than 160 μm). ASR-expansion appeared for particles having diameters greater than 160 μm
171 (Figure 3). However, for the same content of reactive particles, the expansion was smaller for
172 the 160-315 μm reactive particles than for the 315-630 μm reactive ones. The critical particle
173 size that caused ASR-expansions was around 200 and 300 μm . ASR-expansions increased
174 with the size of reactive particles between 0 and 630 μm . The ASR-expansion was very
175 similar for the 315-630 μm particles and for the 630-1250 μm ones. Finally, the larger
176 reactive particles showed lower expansions (Figure 3). This pessimum effect, which has
177 already been observed for other reactive aggregates [10, 13], is assessed in the last part of this
178 paper.

179 The expansion of the mortar is caused by the expansions of the ASR-gels. It can be assumed
180 that this expansion is caused by the volume variation of the aggregate (in presence of gel). For
181 the sake of simplicity, it is assumed in this paper that the mortar expansion due to ASR (ε_{ASR})
182 is proportional to the aggregate expansion (equation 1). For several sizes of reactive particles,
183 the aggregate expansion is the sum of the expansions of all the reactive aggregates.

184

$$185 \quad \varepsilon_{ASR} = k \cdot \sum_{i=1}^{N_{rc}} \varphi_i^{agg} \varepsilon_i^{agg} \quad (1)$$

186 where ε_i^{agg} is the expansion of one reactive aggregate of class i , φ_i^{agg} is the volume fraction of
187 reactive aggregates of class i relative to the mortar volume (total volume of reactive aggregate
188 of class i / total volume of the mortar), N_{rc} is the number of classes of reactive aggregates and
189 k is the fraction of expansion due to ASR related to the expansion of reactive aggregates.

190

191 The mortar expansion is assumed to be due to the aggregate expansion. If $k=1$, the mortar
192 expansion is equal to the aggregate expansion (weighted by the volume fraction of reactive
193 aggregates in the mortar). In reality, k has to be equal to or lower than 1, since the mortar
194 expands less than the aggregate due to the mechanical effect of cement paste. The decrease of
195 the value of the parameter k corresponds to the increase of the restraint of the cement paste on
196 the aggregate. During ASR, when the aggregate swells, the cement paste is subjected to
197 tensile stresses. Therefore, the effect of restraint is limited and the parameter k should not be
198 too small.

199 During the formation of the ASR-gel, a part of the gel can migrate through the porosity close
 200 to the aggregate without causing expansion. Therefore, the aggregate expansion for one
 201 aggregate i can be described by equation 2.

202

$$203 \quad \varepsilon_i^{agg} = \frac{\langle V_i^{gel} - V_i^{poro} \rangle^+}{V_i^{agg}} \quad (2)$$

204 With:

205 - V_i^{agg} : the volume of one reactive particle, $V_i^{agg} = \frac{4}{3}\pi \cdot R_i^3$, where R_i is the radius of the
 206 reactive particle.

207 - $\langle X \rangle^+$: the positive part of X : if $X < 0$, $\langle X \rangle^+ = 0$ otherwise $\langle X \rangle^+ = X$

208 - V_i^{poro} : the volume of the porosity close to the reactive aggregate in which the ASR gel can
 209 migrate without causing expansion. Assuming that the gel can migrate along the
 210 same distance of the aggregate l_c whatever the size of the aggregate (simplifying
 211 hypothesis), the volume of the porosity is given by equation 3, where φ^{void_mortar} is
 212 the porosity of the mortar.

$$213 \quad V_i^{poro} = \frac{4}{3}\pi \cdot ((R_i + l_c)^3 - R_i^3) \cdot \varphi^{void_mortar} \quad (3)$$

214 - V_i^{gel} : the volume of ASR gel formed in only one reactive particle.

215

216 The volume of gel V_i^{gel} is considered as proportional to the alkali content and the reactive
 217 aggregate volume, as defined by equation 4.

218

$$219 \quad V_i^{gel} = \varphi_i^{gel} \cdot V_i^{agg} \quad (4)$$

220 where φ_i^{gel} is the volume fraction of gel related to the particles of class i . φ_i^{gel} can be seen as
 221 the volume of gel (m^3) per m^3 of aggregate: the higher the aggregate content, the higher the
 222 amount of gel. It also implies that for high alkali content, more silica is attacked.

223

224 According to previous results [31] which showed that it was reasonable to use linear
 225 relationships to express the expansions of mortars versus the alkali content and versus the
 226 quantity of reactive particles, it can thus be assumed that φ_i^{gel} is proportional to:

227 - the alkali content of the mortar (AC) minus a threshold of alkalis (AC_{th}) under which no
 228 expansion occurs. Usually, high alkali content implies deeper aggregate attack, and thus a
 229 larger volume of gel per m^3 of reactive aggregate. However, many papers [24-30] have shown
 230 that, for low alkali contents (under a threshold lying between 3 and 5 kg/m^3), no expansion
 231 occurs. The value of AC_{th} used in this work was 3.5 kg/m^3 [31]. φ_{ref}^{gel} is a reference volume
 232 fraction of gel fitted from tests on mortars containing AC_{ref} (alkali content of the mortar in the
 233 first set of experiments - 8.1 kg/m^3).

234 - the volume fraction of the quantity of reactive particles of size i and the quantity of reactive
 235 aggregate in the mortar (expressed as volume fractions φ_i^{agg} and φ_{tot}^{agg}). In fact, the volume of
 236 gel created by the reactive particles of one size depends on the content of the reactive
 237 aggregates of this size compared to the content of all the reactive aggregates of the mortar. If
 238 there are only large particles, all alkalis can react with these particles but when small particles
 239 are added (as in the second set of experiments), the alkali content which reacts with the large
 240 particles has to decrease. It can be assessed by equation 5 for a time corresponding to the end
 241 of the tests.

242 From the above, the expression of the volume fraction of gel φ_i^{gel} can be given by equation 5.

$$243 \quad \varphi_i^{gel} = \varphi_{ref}^{gel} \frac{\langle AC - AC_{th} \rangle^+ \varphi_i^{agg}}{\langle AC_{ref} - AC_{th} \rangle^+ \varphi_{tot}^{agg}} \quad (5)$$

244 With:

245 - φ_{ref}^{gel} : reference volume fraction of gel fitted from tests with AC_{ref}

246 - φ_i^{agg} : volume fraction of reactive aggregates of class i relative to the mortar

247 - φ_{tot}^{agg} : volume fraction of reactive aggregates (total: all classes) relative to the mortar

248 - AC : alkali content of the mortar

249 - AC_{th} : value of the threshold in alkali (taken equal to 3.5 kg/m³),

250 - AC_{ref} : alkali content of the mortar used to fit φ_{ref}^{gel} (8.1 kg/m³),

251

252 The combination of equations 1 to 5 for only one class of reactive particles (first set of
 253 experiments) leads to the equation 6.

$$254 \quad \varepsilon_{ASR} = k \cdot \varphi_i^{agg} \cdot \left[\left\langle \varphi_i^{gel} - \varphi^{void_mortar} \cdot \left(\frac{(R_i + l_c)^3}{R_i^3} - 1 \right) \right\rangle^+ \right] \quad (6)$$

255 With $\varphi_i^{gel} = \varphi_{ref}^{gel}$ since, for the first set of experiments, $AC = AC_{ref} = 8.1$ kg/m³ and $\varphi_i^{agg} = \varphi_{tot}^{agg}$
 256 (only one class of reactive particles).

257

258 In order to carry out this calculation, three parameters must be determined: l_c , φ_{ref}^{gel} and k . In
 259 this paper, several values for k between 0.1 and 1 are considered (for $k = 0.1$, the aggregate
 260 swells 10 times more than the mortars), and l_c and φ_{ref}^{gel} are calculated to minimize the
 261 deviation between the calculated value ε_{ASR} and the measured one. The value calculated using
 262 equation 5 (which is a volumetric deformation) was divided by 3 in order to obtain linear
 263 expansion (comparable to measured expansion on mortars).

264 The results of the calculations of the parameters are given in Table 2 and the calculated
 265 expansions are plotted in Figure 7. Whatever the values of k , all the curves are quite similar,
 266 so only one curve is plotted (named 'Asymptotic expansion model'). For the lower values of

267 k , the values of l_c and φ_{ref}^{gel} are maximal (Table 2). The larger the cement paste restraint is, the
268 larger the volume of ASR-gel must be to obtain significant expansion; and if there is a lot of
269 gel, l_c has to be large to prevent expansion for the small reactive particles. For the values of
270 the parameter k higher than 0.1, the value of the parameter l_c ranges between 11 and 91 μm .
271 Although the cement paste largely restrains the aggregate, this calculation can explain the
272 increase of expansion with the size of the reactive particles.

273

274 To sum up, the model developed in this section assumes that the increase of ASR-expansion
275 with the size of reactive particles can be explained by the effect of the porosity connected to
276 the reactive aggregate. A porous crown of thickness l_c around the reactive aggregate, which is
277 connected to the gel formation site, is defined. The volume of porosity to be filled around
278 each particle of radius R_i before the expansion starts is given by equation 3. Figure 8 shows
279 the total volume of porosity to be filled ($V_i^{poro} \cdot N_i$, in m^3 per m^3 of mortar) when considering
280 the number of reactive aggregate of each size (N_i). On the other hand, the volume of gel was
281 computed according to equations 4 and 5, for which the volume of gel was considered as
282 proportional to the alkali content and the aggregate volume. The expansion of an
283 unconstrained mortar prism was then taken as the volumetric change of the aggregate due to
284 the gel volume not contained in the porous crown (equations 1 and 2). This simple relation
285 allows the final expansion to be plotted against the aggregate radius R_i and the alkali content.

286 The calculation can be generalized for different sizes of reactive aggregates and different
287 alkali contents. Figure 9 shows the expansion of mortar prisms for ($20 < R < 1000 \mu\text{m}$) and (3
288 $< AC < 10 \text{ kg/m}^3$). It can be seen that expansion increases linearly with the alkali content and
289 non-linearly with the aggregate diameter. It could be concluded, abusively, from this figure
290 that large aggregates and large alkali contents should lead to the highest expansion amplitude.
291 However, even if a large aggregate presents a large expansion in this graph, a long test
292 duration is needed in reality to obtain the final expansion amplitude, due to the long diffusion
293 time for alkalis to reach the center of the particle (the porosity of this aggregate is less than
294 1%). In contrast, for small aggregates, alkali ingress is faster and the reaction occurs rapidly,
295 but the porous crown delays the expansion.

296 A pessimum size should exist for which the expansion is maximum for a given duration of
297 test. This pessimum is obtained when the size of the aggregate is large enough to fill the
298 connected porosity and the aggregate is completely attacked by the alkalis (while the larger

299 sizes are not). In order to gain a better understanding of these phenomena, a time-dependent
300 expansion model is proposed in section 4.2.

301

302 4.1.2 Effect of fine reactive aggregate on asymptotic expansion

303 For mortars containing two sizes of reactive particles, the larger the content of reactive
304 aggregate was, the smaller were the ASR-expansions (Figure 6). In fact, the increase of the
305 proportion of reactive aggregate was due to the increase of the smallest reactive particles (0-
306 80 μm), while the proportion of the largest reactive particles (1250-3150 μm) was the same.
307 The previous part showed that the smallest reactive particles did not cause expansion, but the
308 largest ones expanded greatly. As the content of large particles was the same for all the five
309 mortars (for one alkali content), expansions could be expected to be similar. However, the
310 experimentation showed that the expansion decreased with increasing content of the small
311 reactive particles. This effect has already been shown on concrete [32] and can sometimes be
312 explained by the consumption of the alkalis by the small reactive particles. When aggregate
313 powders are dispersed in a cement paste they release silica, resulting in a lowering of the
314 Ca/Si ratio in C-S-H. It has been established that the ability of these low Ca/Si C-S-H to fix
315 alkalis is enhanced. The depletion of free alkalis lowers the pH of the pore solution and,
316 consequently, reduces the attack of reactive aggregates. Finally the expansion is reduced or
317 suppressed. However, it should be noted that this explanation is not satisfactory in all cases:
318 some alkali-releasing mineral admixtures can inhibit the reaction, or sometimes only retard it
319 (e.g. high alkali fly ashes).

320

321 Calculations were performed using equations 1 to 5 for the two alkali contents and the two
322 size classes of the second set of experiments, without any supplementary fitting. Figure 10
323 gives the measured expansions versus the expansions assessed with the model with the
324 parameters determined for $k=1$ in the previous part (Table 2). As shown in Figure 10, the
325 model gives values not too far from the measured expansions. The mean deviation between
326 calculated and measured expansions is about 18%. It can be partly explained by the deviation
327 between the model and the measurements for the largest particle for the parameter determined
328 in the previous part. The value calculated for the largest particle was about 30% higher than
329 the measurement (Figure 7). The overestimation of the expansion of coarse particles thus
330 leads to an overestimate of the expansions of mortars containing mixtures of fine and coarse
331 aggregates.

332 The model uses only proportionality between the parameters of volume of gel, alkali content
 333 and reactive aggregate content. It appears to be efficient for assessing ASR-expansions in this
 334 case for which mix designs and environmental conditions are perfectly known.

335

336 **4.2 Time-dependent expansion model**

337 In order to improve the model, it is decided to use a time-dependent model which allows us to
 338 (take into account) or (explain) the pessimum effect of coarse aggregates. A simplified
 339 diffusion model is chosen, which does not consider the mixture of aggregates of different
 340 sizes.

341 The simplest way to introduce the time effect in the previous model is to model the alkali
 342 ingress kinetics through a simple phenomenological function. For experimental and physical
 343 reasons, a square root function of the time is proposed [3]. The thickness of alkali penetration
 344 from the paste to the center of the aggregate is thus given by equation 7.

$$345 \quad x(t) = R_{ref} \sqrt{\frac{t}{t_{ref}}} \quad (7)$$

346 With:

347 $x(t)$: thickness of alkali penetration at a time t , from the paste to the center of the aggregate

348 R_{ref} : radius of the aggregate used in the mortar for which the reference time t_{ref} is fitted

349 t_{ref} : time necessary for alkali to reach the center of the aggregate of radius R_{ref} , fitted on
 350 experimental results such as $x(t_{ref}) = R_{ref}$. In our case, t_{ref} was fitted using the radius
 351 $R_{ref} = 236 \mu\text{m}$ (mortar M4 – size of aggregate: 315-630 μm). It was assumed that the
 352 time necessary for alkali to reach the center of the aggregate of radius $R_{ref} = 236 \mu\text{m}$
 353 was 170 days (beginning of the asymptotic swelling of Mortar M4, as seen on Figure
 354 2).

355 t : duration of test

356

357 For a given duration t , the volume fraction of an aggregate of radius R_i affected by the
 358 reaction is then given by equation 8.

359

$$360 \quad f(t) = \phi_i^{asr-agg}(t) = \frac{R_i^3 - \left(\langle R_i - x(t) \rangle^+ \right)^3}{R_i^3} \quad (8)$$

361

362 The combination of equations 1 to 5 and 7-8 for only one class of reactive particles leads to
 363 the time-dependent model given by equation 9.

364

$$\begin{aligned}
\varepsilon_{ASR}(t) &= k \cdot \varphi_i^{agg} \cdot \varepsilon_i^{agg}(t) \\
365 \quad &= k \cdot \varphi_i^{agg} \cdot \frac{\langle V_i^{gel} \cdot f(t) - V_i^{poro} \rangle^+}{V_i^{agg}} \\
&= k \cdot \varphi_i^{agg} \cdot \left[\left\langle \varphi_i^{gel} \cdot f(t) - \varphi^{void_mortar} \cdot \left(\frac{(R_i + l_c)^3}{R_i^3} - 1 \right) \right\rangle^+ \right]
\end{aligned} \tag{9}$$

366 With $\varphi_i^{gel} = \varphi_{ref}^{gel}$ (equation 5) since, for the first set of experiments, $AC = AC_{ref} = 8.1 \text{ kg/m}^3$
367 and $\varphi_i^{agg} = \varphi_{tot}^{agg}$ (only one class of reactive particles).

368

369 In fact, in order to model the alkali consumption in a mixture, it is necessary to consider
370 explicitly the decrease of the alkali content in the mortar due to the simultaneous consumption
371 by all aggregates of different sizes. This phenomenon is a problem of coupled diffusion, too
372 hard to be considered in a simple “summary model”. It is treated in detail in other works still
373 in progress (and also in works such as Poyet et al. [6]).

374

375 Figure 7 compares the ASR-expansion of mortars containing one size of reactive particles
376 (M1 to M6) with the asymptotic expansion model (section 4.1) and the time-dependent model
377 developed in this section. It is observed that the time-dependent model represents the
378 variation of the experimental data well, without any supplementary fitting of the parameters
379 (except l_c and φ_{ref}^{gel} calculated from the first model).

380 Figure 11 generalizes the calculations of the expansion for various alkali contents (AC) and
381 aggregate sizes (R) for test durations of 50 and 500 days. It shows that, for a sufficient
382 amount of alkali, the dependence of the expansion on the aggregate size can be seen as a
383 pessimum effect. For these simulations, the expansion at 50 days is maximal for a reactive
384 aggregate radius around 200-250 μm . This maximal expansion depends on the alkali content;
385 it moves to 350 μm if alkali content is close to 6 kg/m^3 . After longer times, the pessimum size
386 increases (500-600 μm), since the alkali has had time to progress inside the aggregate.

387 Figure 12 gives the expansion curves for test durations up to 500 days and several aggregate
388 radii, the alkali content being 8.1 kg/m^3 . This Figure shows that expansion curves are
389 stabilized only for aggregates having radii of less than around 300 μm .

390

391 **4.3 A synthesis of the part model and discussion**

392 The asymptotic expansion and time dependent models summarize the main experimental
393 observations given in the previous sections. They allow some important phenomena linked to
394 the size of reactive aggregate to be interpreted easily. Firstly, the decrease of expansion for

395 small aggregates is interpreted through the porous crown effect. Secondly, the slower
396 expansion rate for large aggregates is explained using the alkali ingress kinetics.

397 It is interesting to note that the understanding of the pessimum effect of reactive aggregate
398 size can be useful when fixing the parameters of accelerated laboratory tests. The model
399 highlights the possibility of maximizing expansion, and consequently minimizing the test
400 duration, by appropriate choices of both the alkali content and the aggregate size. This size
401 must be sufficient to attenuate the connected porosity effect without making the duration of
402 the test too long.

403 A direct application of this interpretation could be an original procedure aimed at minimizing
404 the accelerated expansion test duration. For example, the authors are currently working on
405 such a test clarification: it consists in extracting aggregates from an affected concrete,
406 crushing them, and keeping only crushed particles of a given size. The mortars made with
407 these aggregates (and an addition of alkalis) allow the potential for residual expansion of the
408 concrete to be evaluated indirectly in the shortest possible time. Of course, this type of test
409 must be combined with a particular model allowing the residual potential of the uncrushed
410 aggregate in the concrete to be evaluated. Research is still in progress concerning this last
411 topic.

412

413 **5 CONCLUSION**

414 This paper has presented the experimental measurements performed on 16 different mix-
415 designs containing reactive siliceous limestone with special attention being paid to the
416 proportions of alkalis ($\text{Na}_2\text{O}_{\text{eq}}$) and reactive silica in the mixtures. It has been shown that:

417 - small reactive particles (under about 160 μm) do not cause expansion while coarse particles
418 (0.63-1.25 mm) show the largest expansion (0.33%).

419 - ASR-expansion decreases with the amount of small particles when the mortars contain two
420 sizes of aggregates (0-80 and 1250-3150 μm).

421

422 A first model shows that these results can be explained by the migration of ASR-gel in the
423 porosity very close the reactive aggregate (less than 10 μm). The volume fraction of gel with
424 respect to reactive aggregate has been considered as proportional to the alkali content of the
425 mortar minus a threshold alkali content and to the proportion of reactive aggregates of each
426 size compared to the content of all the reactive aggregates in the mortar. With these
427 assumptions, the model predicts the expansions of the mortars containing two sizes of reactive
428 aggregates.

429 In a second model, a time dependence of the expansion was introduced. It has been shown
430 that, for a given duration of test and a given alkali content, the expansion is maximized for a
431 specific range of aggregate size, which can be seen as a pessimum effect.

432

433 This approach allows a better understanding of the effects of aggregate size and alkali content
434 on the expansion of mortars. It could also be useful for fixing the parameters of accelerated
435 laboratory tests (maximizing expansion and minimizing duration of test). These tests and
436 models will be used as a basis for the development of future models to assess the potential
437 expansion of concrete containing alkali-reactive aggregates.

438

439

440 **ACKNOWLEDGEMENTS**

441 The authors are grateful to EDF for supporting this work.

442

443 **REFERENCES**

- 444 [1] B. Capra, A. Sellier, Orthotropic modelling of alkali-aggregate reaction in concrete
445 structures: numerical simulations, *Mechanics of Materials* 35 (8) (2003) 817-830.
- 446 [2] A. Sellier, E. Bourdarot, S. Multon, M. Cyr, E. Grimal, 2007, Assessment of the
447 residual expansion for expertise of structures affected by AAR, 10th International
448 Conference on Alkali-Aggregate Reaction, Broekmans M.A.T.M. and Wigum B.J.
449 (Eds), Trondheim, Norway, 2008, pp.1004-1013.
- 450 [3] Y. Furusawa, H. Ohga, T. Uomoto, An analytical study concerning prediction of
451 concrete expansion due to Alkali-Silica Reaction, 3rd CANMET/ACI International
452 Conference on Durability of Concrete, Nice, France, 1994, pp.757-779.
- 453 [4] A. Sellier, J.-P. Bournazel, A. Mébarki, Modelling the alkali aggregate reaction within a
454 probabilistic frame-work, 10th International Conference on Alkali-Aggregate Reaction,
455 Shayan A. (Ed), Melbourne, Australia, 1996, pp.694-701.
- 456 [5] Z.P. Bazant, A. Steffens, Mathematical model for kinetics of alkali silica reaction in
457 concrete, *Cement and Concrete Research* 30 (3) (2000) 419-428.
- 458 [6] S. Poyet, A. Sellier, B. Capra, G. Foray, J.-M. Torrenti, H. Cognon, E. Bourdarot,
459 Chemical modelling of Alkali Silica reaction: Influence of the reactive aggregate size
460 distribution, *Materials and Structures* 40 (2) (2007) 229–239.
- 461 [7] A. Suwito, W. Jin, Y. Xi, C. Meyer, A mathematical model for the pessimum effect of
462 ASR in concrete, *Concrete Science and Engineering* 4 (13) (2002) 23-34.
- 463 [8] D. McConnell, R.C. Mielenz, W.Y. Holland, K.T. Greene, Cement-aggregate reaction
464 in concrete, *Journal of the American Concrete Institute, Proceedings* Vol.44, No.2,
465 1947, pp.93-128.
- 466 [9] T.M. Kelly, L. Schuman, F.B. Hornibrook, A study of alkali-silica reactivity by means
467 of mortar bar expansions, *Journal of the American Concrete Institute, Proceedings*
468 Vol.45, No.1, 1948, pp.57-80.
- 469 [10] S. Diamond, N. Thaulow, A study of expansion due to alkali-silica reaction as
470 conditioned by the grain size of the reactive aggregate, *Cement and Concrete Research*
471 4 (4) (1974) 591-607.

- 472 [11] D.W. Hobbs, W.A. Gutteridge, Particle size of aggregate and its influence upon the
473 expansion caused by the alkali-silica reaction, Magazine of Concrete research 31 (109)
474 (1979) 235-242.
- 475 [12] M. Kawamura, K. Takemoto, S. Hasaba, Application of quantitative EDXA analyses
476 and microhardness measurements to the study of alkali-silica reaction mechanisms, 6th
477 International Conference of Alkalies in Concrete, Idorn G.M. and Rostam S. (Eds),
478 Copenhagen, Denmark, 1983, pp.167-174.
- 479 [13] X. Zhang, G.W. Groves, The alkali-silica reaction in OPC/silica glass mortar with
480 particular reference to pessimum effects, Advances in Cement Research, 3 (9) (1990) 9-
481 13.
- 482 [14] L. Hasni, Y. Gallias, M. Salomon, Appréciation des risques d'alcali- réaction dans les
483 bétons de sable, Rapport de recherche n°41020, Centre Expérimental de Recherches et
484 d'Etudes du Bâtiment et des Travaux Publics (CEBTP), St-Rémy- lès-Chevreuses, 1993,
485 53p.
- 486 [15] B.J. Wigum, W.J. French, Sequential examination of slowly expanding alkali-reactive
487 aggregates in accelerated mortar bar testing, Magazine of Concrete research 48 (177)
488 (1996) 281-292.
- 489 [16] C. Zhang, A. Wang, M. Tang, B. Wu, N. Zhang, Influence of aggregate size and
490 aggregate size grading on ASR expansion, Cement and Concrete Research 29 (9) (1999)
491 1393-1396.
- 492 [17] T. Kuroda, S. Inoue, A. Yoshino, S. Nishibayashi, Effects of particle size, grading and
493 content of reactive aggregate on ASR expansion of mortars subjected to autoclave
494 method, 12th International Conference on Alkali-Aggregate Reaction in Concrete, Tang
495 M. and Deng M. (Eds), Beijing, China, 2004, pp.736-743.
- 496 [18] K. Ramyar, A. Topal, O. Andic, Effects of aggregate size and angularity on alkali-silica
497 reaction, Cement and Concrete Research 35 (11) (2005) 2165-2169.
- 498 [19] M. Moisson, M. Cyr, E. Ringot, A. Carles-Gibergues, Efficiency of reactive aggregate
499 powder in controlling the expansion of concrete affected by alkali-silica reaction (ASR),
500 12th International Conference on Alkali-Aggregate Reaction in Concrete, Tang M. and
501 Deng M. (Eds), Beijing, China, 2004, pp.617-624.
- 502 [20] AFPC–AFREM (Association Française Pour la Construction – Association Française de
503 Recherche et Essais sur les Matériaux de construction), Durabilité des bétons. Méthodes
504 recommandées pour la mesure des grandeurs associées à la durabilité. Mesure de la
505 masse volumique apparente et de la porosité accessible à l'eau. Compte-Rendu des
506 Journées Techniques, Toulouse, 11-12 December 1997, pp.121–124.
- 507 [21] T.N. Jones, A.B. Poole, Alkali-silica reaction in several U.K. concretes: the effect of
508 temperature and humidity on expansion, and the significance of ettringite development,
509 7th International Conference on Alkali-Aggregate Reaction in Concrete, Grattan-Bellew
510 P.E. (Ed), Ottawa, Canada, 1986, pp.446-450.
- 511 [22] P.K. Mukherjee, J.A. Bickley, Performance of glass as concrete aggregates, 7th
512 International Conference on Alkali-Aggregate Reaction in Concrete, Grattan-Bellew
513 P.E. (Ed), Ottawa, Canada, 1986, pp.36-42.
- 514 [23] A. Carles-Gibergues, M. Cyr, Interpretation of expansion curves of concrete subjected
515 to accelerated alkali-aggregate reaction (AAR) tests, Cement and Concrete Research 32
516 (5) (2002) 691-700.
- 517 [24] Kodama K., Nishino T., Observation around the cracked region due to alkali-aggregate
518 reaction by analytical electron microscope, 7th International Conference on Alkali-
519 Aggregate Reaction in Concrete, Grattan-Bellew P.E. (Editor), Ottawa, Canada, 1986,
520 pp.398-402.

- 521 [25] Kennerley R.A., St John D.A., Smith L.H., A review of thirty years of investigation of
522 the alkali-aggregate reaction in New Zealand, 5th International Conference on Alkali-
523 Aggregate Reaction in Concrete, National Building Research Institute of the CSIR
524 (Editor), Cape Town, South Africa, 1981, S252/12, 9p.
- 525 [26] Oberholster R.E., Alkali reactivity of siliceous rock aggregates: diagnosis of the
526 reaction, testing of cement and aggregate and prescription of preventive measures, 6th
527 International Conference on Alkali-Aggregate Reaction in Concrete, Idorn G.M. and
528 Rostam S. (Editors), Copenhagen, Denmark, 1983, pp.419-433.
- 529 [27] Hobbs D.W., Alkali-silica reaction in concrete, Thomas Telford, London, 1988.
- 530 [28] Rogers C.A., Hooton R.D., Reduction in mortar and concrete expansion with reactive
531 aggregates due to alkali leaching, Cement, Concrete and Aggregates, 13 (1) (1991) 42-
532 49.
- 533 [29] Thomas M.D.A., Blackwell B.Q., Nixon P.J., Estimating the alkali contribution from fly
534 ash to expansion due to alkali-aggregate reaction in concrete, Magazine of Concrete
535 Research, 48 (177) (1996) 251-264.
- 536 [30] Shehata M.H., Thomas M.D.A., The effect of fly ash composition on the expansion of
537 concrete due to alkali-silica reaction, Cement and Concrete Research, 30 (7) (2000)
538 1063-1072.
- 539 [31] S. Multon, M. Cyr, A. Sellier, N. Leklou, L. Petit, Coupled effects of aggregate size and
540 alkali content on ASR expansion, Cement and Concrete Research 38 (3) (2008) 350-
541 359.
- 542 [32] J.S. Guédon-Dubied, G. Cadoret, V. Durieux, F. Martineau, P. Fasseu, V. van
543 Overbecke, Study on Tournai limestone in Antoing Cimescaut Quarry. Petrological,
544 chemical and alkali reactivity approach, 11th International Conference on Alkali-
545 Aggregate Reaction in Concrete, Bérubé M.A. Fournier B. Durand B. (Eds), Quebec
546 City, Canada, 2000, pp.335-344.
547
548
549

- 550 Notation:
- 551 ε_{ASR} : expansion of mortar due to ASR
- 552 ε_i^{agg} : expansion of one reactive aggregate of class i
- 553 N_{rc} : number of classes of reactive aggregates
- 554 k : fraction of expansion due to ASR related to the expansion of reactive aggregates
- 555 l_c : distance of migration of the gel from the periphery of the aggregate
- 556 ϕ_i^{agg} : volume fraction of reactive aggregates of class i relative to the mortar
- 557 ϕ_{tot}^{agg} : volume fraction of reactive aggregates (total: all classes) relative to the mortar
- 558 ϕ_i^{gel} : volume fraction of gel related to the particles of class i ($\phi_i^{gel} = V_i^{gel} / V_i^{agg}$)
- 559 ϕ_{ref}^{gel} : reference volume fraction of gel fitted from tests with AC_{ref}
- 560 ϕ^{void_mortar} : porosity of the mortar
- 561 V_i^{gel} : volume of ASR gel formed in only one reactive particle of class i
- 562 V_i^{poro} : volume of the porosity close to a reactive aggregate of class i, from which ASR
- 563 gel can migrate without causing expansion
- 564 V_i^{agg} : volume of one reactive particle of class i
- 565 R_i : mean radius of reactive particle of class i
- 566 AC : alkali content of the mortar
- 567 AC_{th} : value of the threshold in alkali (taken equal to 3.5 kg/m³),
- 568 AC_{ref} : alkali content of the mortar used to fit ϕ_{ref}^{gel} (8.1 kg/m³),
- 569 $x(t)$: thickness of alkali penetration at a time t , from the paste to the center of the aggregate
- 570 R_{ref} : radius of the aggregate used in the mortar for which the reference time t_{ref} is fitted
- 571 t_{ref} : time necessary for alkali to reach the center of the aggregate of radius R_{ref} , fitted on
- 572 experimental results such as $x(t_{ref}) = R_{ref}$
- 573 t : duration of test
- 574 $\phi_i^{asr-agg}(t)$: volume fraction of an aggregate of class i affected by ASR at time t
- 575
- 576
- 577
- 578

Table 1 - Chemical composition of cement and aggregates (% 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 |
| Reactive siliceous limestone (1.25-3.15 mm) | 20.0 | 1.3 | 0.6 | 40.6 | 1.2 | 0.4 | 0.4 | 0.7 | 0.3 | 34.7 |

- 579
- 580
- 581
- 582
- 583

Table 2 - Model parameters

| | | | | | |
|-------------------------|-------|-------|-------|-------|-------|
| k | 0.1 | 0.25 | 0.5 | 0.75 | 1 |
| l_c (μm) | 91 | 41 | 22 | 15 | 11 |
| ϕ_{ref}^{gel} | 0.651 | 0.263 | 0.132 | 0.088 | 0.066 |

- 584

585

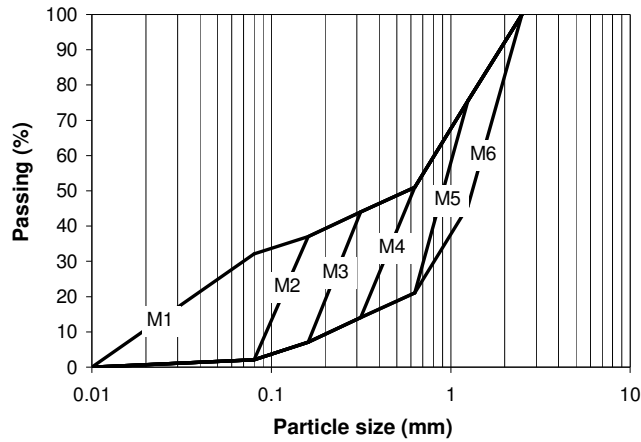


Figure 1 - Particle size distributions of mortars M1 to M6.

586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603

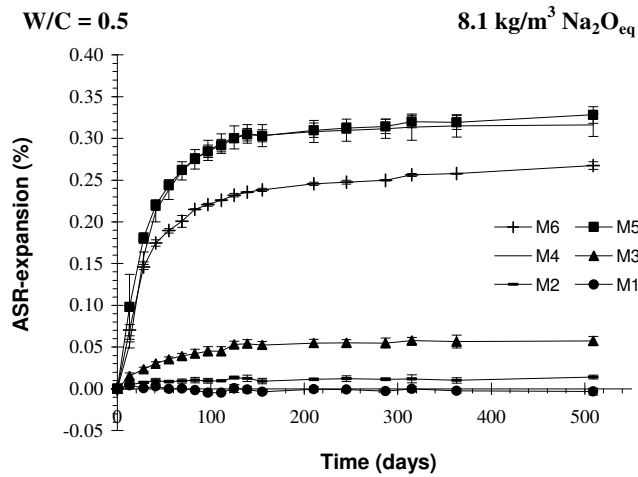
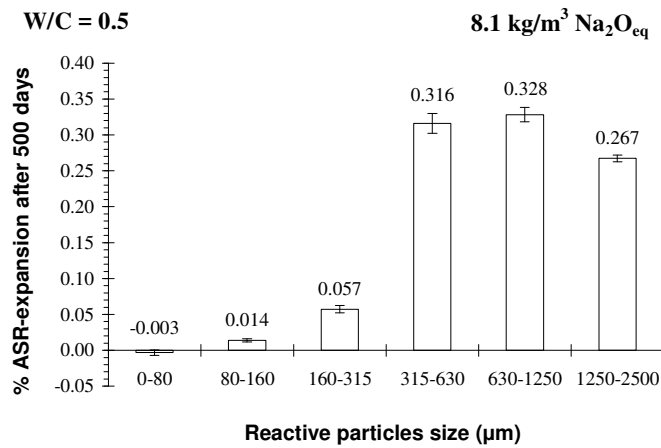


Figure 2 - ASR-expansions of mortars containing 30% of reactive particles of size 0-80 (M1), 80-160 (M2), 160-315 (M3), 315-630 (M4), 630-1250 (M5), 1250-2500 μm (M6) and 70% of continuous 0-2500 μm non-reactive sand.

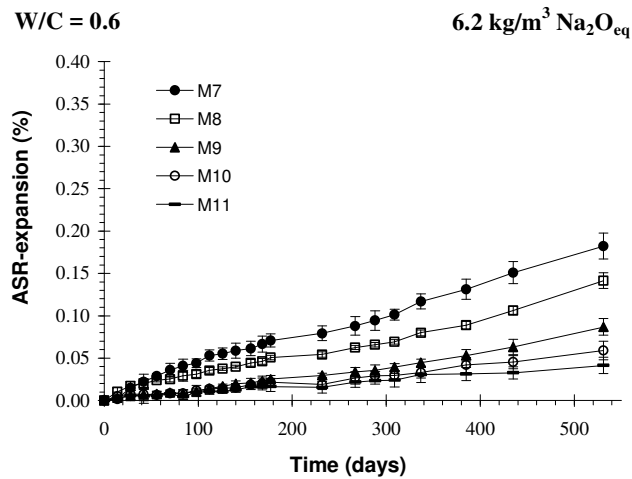
604
605
606
607
608
609

610



611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628

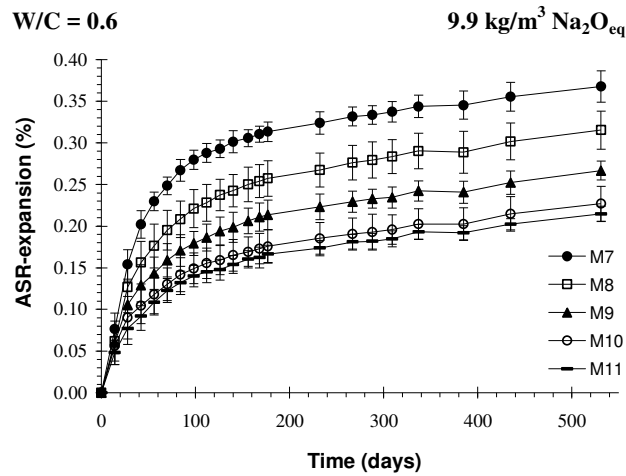
Figure 3 - ASR-expansions of mortars containing 30% of reactive particles of size 0-80 (M1), 80-160 (M2), 160-315 (M3), 315-630 (M4), 630-1250 (M5), 1250-2500 μm (M6) and 70% of continuous 0-2500 μm non-reactive sand after 500 days at 60°C and 95% RH.



629
630
631
632
633
634

Figure 4 - ASR-expansions of mortars containing variable proportions of reactive aggregates (mix of reactive particles of two sizes: 0-80 μm and 1250-3150 μm) for 6.2 kg of alkalis per kg of mortar.

635



636

637

638 Figure 5 - ASR-expansions of mortars containing various reactive aggregate contents (mix of
639 reactive particles of two sizes: 0-80 μm and 1250-3150 μm) for 9.9 kg of alkalis per kg of
640 mortar.

641

642

643

644

645

646

647

648

649

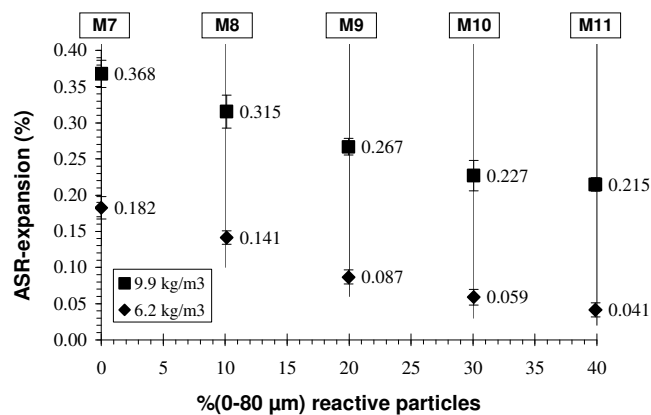
650

651

652

653

654

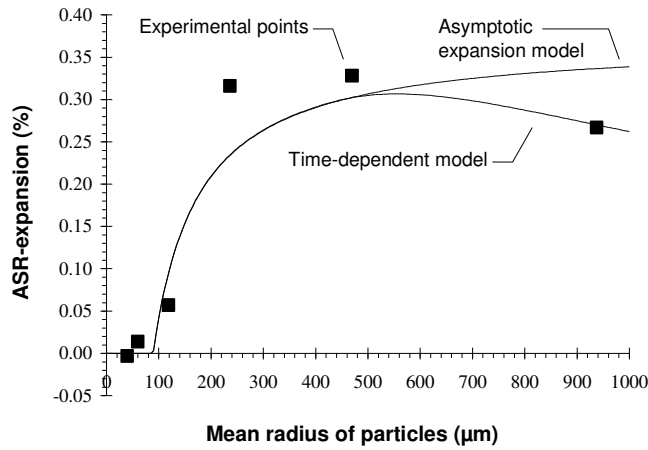


655

656

657 Figure 6 - ASR-expansions at 500 days of mortars containing various reactive aggregates
658 contents (mix of reactive particles of two sizes: 0-80 μm and 1250-3150 μm) for 6.2 and 9.9
659 kg of alkalis per kg of mortar. Effect of the amount of fine (0-80 μm) reactive particles.
660

661



662

663

664

665

666

667

668

669

670

671

672

673

674

675

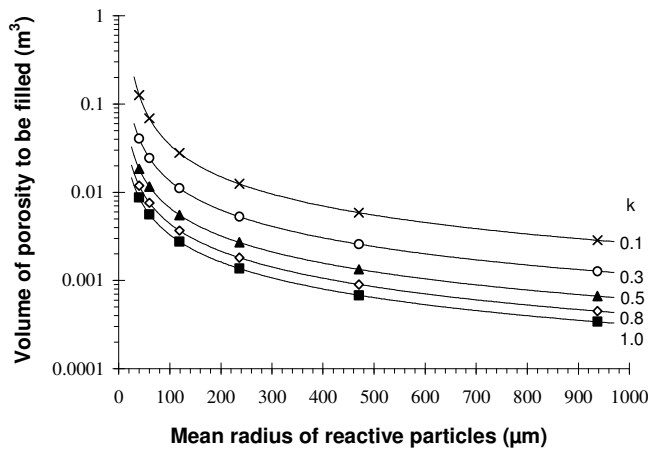
676

677

678

679

Figure 7 - ASR-expansion of mortars containing one size of reactive particles (M1 to M6) versus mean reactive particle size: comparison between experiments, asymptotic expansion model (section 4.1) and time-dependent model (section 4.2) (*data: k , l_c and ϕ_{ref}^{gel} = any column of Table 2, $\phi_{void_mortar}^{void} = 0.17$, $AC_0 = 8.1 \text{ kg/m}^3$, $AC_{th} = 3.5 \text{ kg/m}^3$).*



680

681

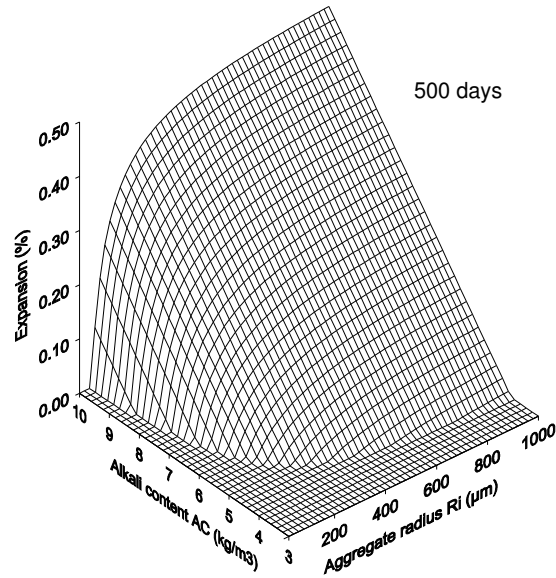
682

683

684

Figure 8 – Volume of porosity to be filled ($V_i^{poro} \cdot N_i$, in m^3 per m^3 of mortar on a logarithmic scale) when considering the number of reactive aggregate of each size (N_i)

685



686

687

688 Figure 9 - Long-term expansion (t=500 days) versus aggregate radius (R) and initial alkali
689 content (AC) in mortars, calculated using the asymptotic expansion model (*data: $k=1, l_c=11$*

690

$$690 \mu m, \varphi_{ref}^{gel} = 0.066, \varphi^{void_mortar} = 0.17, AC_0 = 8.1 \text{ kg/m}^3, AC_{th} = 3.5 \text{ kg/m}^3).$$

691

692

693

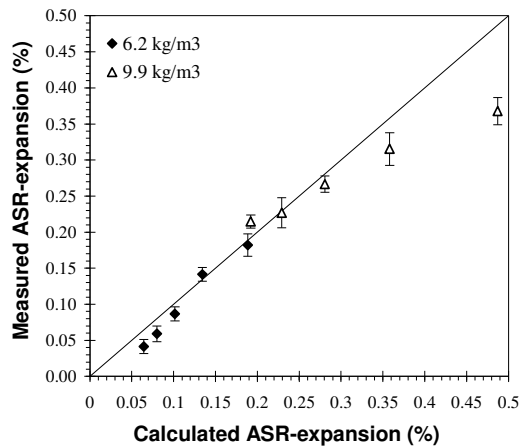
694

695

696

697

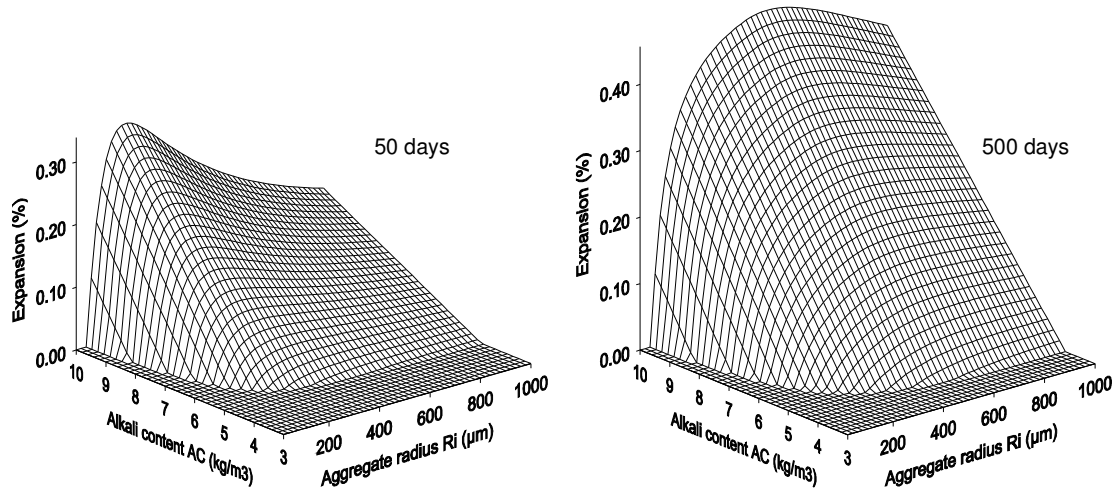
698



699

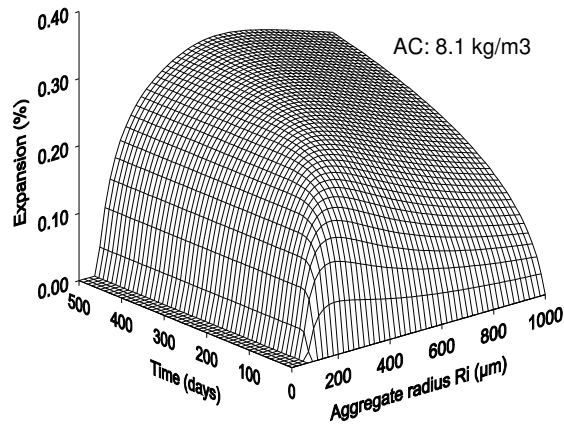
700

701 Figure 10 - Comparison between the expansions calculated using the asymptotic expansion
702 model and the measured expansions, for mortars containing two sizes of reactive particles.
703



704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720

Figure 11 - Expansion versus alkali content (AC) and aggregate size (R) for test durations of 50 and 500 days, calculated using the time-dependent model (*data: $k=1$, $l_c=11 \mu\text{m}$, $\phi_{ref}^{gel}=0.066$, $\phi^{void_mortar}=0.17$, $AC_0=8.1 \text{ kg/m}^3$, $AC_{th}=3.5 \text{ kg/m}^3$, $R_{ref}=236 \mu\text{m}$, $t_{ref}=170 \text{ days}$).*)



721
722
723
724
725

Figure 12 - Expansion curve simulations for different aggregate diameters, calculated using the time-dependent model (*data: $k=1$, $l_c=11 \mu\text{m}$, $\phi_{ref}^{gel}=0.066$, $\phi^{void_mortar}=0.17$, $AC=8.1 \text{ kg/m}^3$, $AC_0=8.1 \text{ kg/m}^3$, $AC_{th}=3.5 \text{ kg/m}^3$, $R_{ref}=236 \mu\text{m}$, $t_{ref}=170 \text{ days}$).*)