



**HAL**  
open science

# Influence of the distribution of expansive sites in aggregates on microscopic damage caused by alkali-silica reaction: Insights into the mechanical origin of expansion

Taito Miura, Stéphane Multon, Yuichiro Kawabata

## ► To cite this version:

Taito Miura, Stéphane Multon, Yuichiro Kawabata. Influence of the distribution of expansive sites in aggregates on microscopic damage caused by alkali-silica reaction: Insights into the mechanical origin of expansion. *Cement and Concrete Research*, 2021, 142, pp.106355. 10.1016/j.cemconres.2021.106355 . hal-03207753

**HAL Id: hal-03207753**

**<https://hal.insa-toulouse.fr/hal-03207753>**

Submitted on 27 Sep 2023

**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 **Title:** Influence of the distribution of expansive sites in aggregates on microscopic  
2 damage caused by alkali-silica reaction: Insights into the mechanical origin of expansion

3  
4 **Authors:** Taito Miura<sup>\*1</sup>, Stephane Multon<sup>2</sup>, Yuichiro Kawabata<sup>3</sup> (\* Corresponding Author)

5 **Affiliation:**

6 1: Department of Civil Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi,  
7 464-8603, Japan

8 2: LMDC, Université de Toulouse, INSA/UPS Génie Civil, 135 Avenue de Rangueil, 31077  
9 Toulouse cedex 04, France

10 3: Port and Airport Research Institute, 3-1-1, Yokosuka, Kanagawa, 239-0826, Japan

11 **Email Addresses:** t.miura@civil.nagoya-u.ac.jp (T. Miura), multon@insa-toulouse.fr (S.  
12 Multon), kawabata-y@p.mpat.go.jp (Y. Kawabata)

13  
14 **Abstract:**

15 The origin of damage in concrete due to the alkali-silica reaction (ASR) is attributed to the  
16 expansion site in the aggregate. To investigate the cracking process of the aggregate during  
17 ASR and its consequences on concrete damage, the effect of the distribution of the expansive  
18 sites in the aggregate on ASR expansion and the crack patterns must be evaluated. Thus, in  
19 this study, a mesoscale discrete model was applied to ASR modeling to represent the  
20 propagation of cracking during ASR accurately. The distribution of the expansive sites in the  
21 aggregate was based on the gel pocket and reaction rim models, which are two ASR  
22 mechanisms reported in the literature. These two expansion models highlight the different  
23 crack patterns obtained based on the aggregate characteristics. Further, the expansion

24 cracking processes determined based on the gel pocket and reaction rim models are consistent  
25 with the evolution of cracking with the expansion level.

26

27 **Keywords:** *Alkali-Silica Reaction (ASR), Cracking, Expansion, Expansive site,*  
28 *Mesoscale discrete model*

29

## 30 **1. Introduction**

31 When concrete structures are damaged by the alkali-silica reaction (ASR), structural  
32 performance is degraded due to the extensive expansion. The ASR expansion is attributed to  
33 the dissolution of reactive silica minerals in aggregates that form an alkali-silica gel (ASR gel).  
34 A conventional mechanism that induces the expansion of ASR gel is the swelling of ASR gel  
35 caused by the imbibition of water [1]. However, the cause behind the expansion of the ASR gel  
36 remains controversial [2]. A recent study reported that the water absorption capacity of ASR  
37 gels synthesized from concrete is considerably similar to that of calcium silicate hydrate (C-S-  
38 H), and the moisture supply to ASR products cannot be held responsible for ASR expansion  
39 [3]. Regardless of the ASR gel expansion mechanism, the aggregate and surrounding cement  
40 paste demonstrate mechanical responses such as deformation and cracking caused by the  
41 expansive pressure exerted by the ASR gel. These responses vary from aggregate to  
42 aggregate, and they are dependent on the microstructural localization of the reaction. Thus, it  
43 is important to elucidate the effect of the spatial distribution of expansive sites on the  
44 microscopic damage in terms of the expansion mechanism.

45 Several expansion models have been proposed for the microstructural localization of  
46 ASR gel expansive sites. Among these models, Ichikawa's model (reaction rim model: the

47 origin of the expansion is inside the rim in the reactive aggregate [4]) and Dunant's model (gel  
48 pocket model: the origin of expansion is randomly distributed inside the aggregate [5]) present  
49 two different approaches based on the microscopic observations of aggregates with different  
50 petrographic characteristics [4–7]. Both models assume that expansive pressure is exerted at  
51 the reaction site (in situ expansion at the reaction site) when the site is well constrained.

52 The precise modeling of cracking in aggregate and concrete during ASR requires the  
53 use of mesoscale discrete models. In this study, a mesoscale discrete model was used to  
54 model the aggregate particles and mortar phase. The model was developed based on a 3D-  
55 Rigid Body Spring Model (3D-RBSM) [8]. The use of mesoscale modeling for quasi-brittle  
56 materials can lead to numerical instabilities. However, 3D-RBSM is a powerful tool for  
57 evaluating damage mechanisms related to cracks with high stability and accuracy [8]. Using  
58 this model, the effect of the spatial distribution of the expansive sites on microscopic damage—  
59 especially cracking propagation due to ASR—was investigated based on the leading ASR  
60 expansion models.

61

## 62 **2. Literature Review and Analytical Objectives**

### 63 **2.1 Evidence from petrographic observations**

#### 64 **2.1.1 Spatial location of expansion**

65 ASR expansion is accompanied by cracking in the aggregate and paste. Cracking  
66 patterns differ and depend on the types of reactive aggregates. The current understanding is  
67 that confinement is necessary for the ASR gel to exert expansive pressure, and the aggregate  
68 itself plays this role; thus, the expansive pressure always increases within the aggregate and  
69 the cracks originate from the aggregate and extend to the paste.

70 After the cracking of the aggregate, the ASR gel may be free from confinement. While  
71 the ASR gel can exude through the cracks without expansion, a substitutional reaction between  
72 Na and Ca occurs simultaneously [4, 9]. This reaction results in the solidification of the ASR  
73 gel in the cracks. Kawabata et al. [9] reported that the solidified ASR gel (similar to C-S-H gel)  
74 provides further confinement. The solidification of ASR gel at the interface prevents additional  
75 ASR gel from exuding from the aggregate, and this can result in an accumulation of pressure  
76 and lead to further crack opening/propagation. A recent study by Shi et al. suggested the  
77 possibility that the formation of Ca-rich ASR products at the interface act as a plug that restrains  
78 the extrusion of ASR gel [10].

### 79 **2.1.2 Crack pattern inside the aggregate**

80 Cracks within the aggregate provide important information that can help indicate the  
81 location of the origin of the expansion. With respect to the crack pattern inside the aggregate,  
82 Sanchez et al. [11] attempted to classify the types of cracks inside aggregates based on the  
83 type of reactive rocks. Based on prior research, they divided the cracking mechanism into three  
84 types: 1) reaction at the interfacial transition zone (ITZ) of nonporous aggregates; 2) reaction  
85 caused by the diffusion of alkali in the aggregate; and 3) reaction at the vein where dissolution  
86 of silica occurs inside aggregates [12]. Models studied in the present study were classified  
87 according to 2). Further, Sanchez et al. proposed an evaluation of the advancement of the ASR  
88 cracking process inside an aggregate using an expansion level. Two types of cracks are  
89 observed: a “sharp crack” and an “onion skin crack”. Sharp cracks are likely to pass through  
90 aggregates while an onion skin crack propagates in the circumferential direction of aggregates.  
91 As the expansion strain increases, sharp cracks propagate into adjacent parts of the aggregate  
92 or into the surrounding cement paste, thereby forming a crack network. For onion skin cracks,

93 the crack reaches the ITZ and propagates into the cement paste. Sanchez et al. commented  
94 that these cracks would not always be generated simultaneously. The type of crack—either  
95 sharp or onion skin—is dependent on the type of rock. Their observations indicated that sharp  
96 cracks can be easily observed in sedimentary and metamorphic rocks. The crack is then easily  
97 generated at the porous areas of the aggregate. However, onion skin cracks can be observed  
98 when alkali metal ions diffuse uniformly into the aggregate. Based on the experimental results  
99 of Ichikawa et al. [4] and Kawabata et al. [9], onion skin cracks tend to appear with highly  
100 reactive andesite.

101

## 102 **2.2 ASR expansion-mechanism-based models**

103 As indicated in the former section, different distributions of the origin of expansion in  
104 aggregates caused by the type of rock strongly influence the ASR mechanisms. In particular,  
105 the ASR gel accumulates at certain sites inside the aggregate with increasing pressure, thereby  
106 leading to the manifestation of cracks. However, an important question that needs to be  
107 emphasized on is the link between the origins of the expansive pressure and the resulting crack  
108 pattern inside the aggregate. Thus, the clarification of the manifestation mechanism of  
109 aggregate cracking leads to a discussion of the origins of expansion inside the aggregate, and  
110 this knowledge can reinforce the understanding of the ASR expansion mechanism.

111 Two mechanism-based models of ASR expansion can be used to explain how the  
112 expansion pressure is exerted within the aggregate: the gel pocket model and the reaction rim  
113 model. In the gel pocket model, the random location of a reactive site—a “gel pocket”—is  
114 explicitly defined; expansive pressure forms at this gel pocket. In contrast, in the reaction rim  
115 model, the heterogeneity of the reactive aggregate is not considered, instead the reaction rim

116 that forms at the inner surface of the aggregate is considered. Expansive pressure is exerted  
117 inside the reaction rim. The details of these models are described with reference to  
118 experimental observations below.

119 The evidence for the gel pocket model has been found from extensive experimental data  
120 using SEM images (e.g., Ben Haha et al. [6] and Ponce et al. [7]). These experimental  
121 observations indicate that reactive phases presumed as the origins of expansion are randomly  
122 distributed inside an aggregate.

123 In the reaction rim model [4], expansion is the consequence of the diffusion of alkali and  
124 ASR-gels of different compositions. First, based on the surface reactions, Na-rich ASR gel is  
125 produced by the reaction between alkalis and reactive aggregate. Second, a Ca-rich ASR gel  
126 is produced by replacing the Na in the ASR gel with Ca from the paste. The Ca-rich ASR gel is  
127 relatively dense and of similar composition to C-S-H, thereby forming a reaction rim at the inner  
128 surface of the reactive aggregate. The reaction rim only permits alkali metal ions to transfer  
129 into the aggregate; the transfer of the Na-rich ASR gel precipitated inside the aggregate to the  
130 outside of the rim is not permitted. Because of further penetration of the alkali metal ions into  
131 the inner aggregate, the Na-rich ASR gel accumulates inside the rim and the expansion  
132 pressure is exerted gradually. This expansion pressure induces cracks inside the aggregate  
133 uniformly, and the crack propagates to the mortar.

134

### 135 **2.3 ASR material modeling**

136 Analytical methods for simulating the ASR expansion behavior at the material scale with  
137 advanced models have been proposed in the literature [13–21], with the current modeling

138 focused on chemical aspects, mechanical aspects, or a combination of chemical and  
139 mechanical mechanisms.

140 ASR advancement can be evaluated in terms of factors of influence related to the ASR  
141 gel production process (i.e., amount of alkalis, reactive silica, calcium, temperature, and  
142 humidity). Modeling the reaction process often assumes a progression from the aggregate  
143 surface to the core, similar to an external attack where transport would be predominant.  
144 However, recent developments have demonstrated the importance of considering the  
145 combination of alkali and moisture transport with the kinetics of reactive mechanisms [18, 21]  
146 to be representative of the observations of damaged concrete [6, 7]. Macroscopic expansion is  
147 then calculated according to the change in the amount of ASR gel over time to evaluate the  
148 range of expansion strain or induced pressure.

149 At the material scale, differences between the models are caused by the method used  
150 to describe the concrete. As concrete is a multiphase material, macroscopic expansion can be  
151 calculated based on different numerical approaches using homogenization principles or a  
152 discretization of the material. The accuracy of the estimated expansion and cracking depends  
153 on the precision of the concrete description and the combination of known ASR-phenomena.

154 The objective of homogenization approaches is to obtain a numerical assessment of  
155 expansion and damage [16, 19] that can be integrated into nonlinear finite element models to  
156 assess the structural performance of ASR-damaged structures. With mesoscale discrete  
157 models, aggregate particles are directly meshed and modeled to reproduce and comprehend  
158 the mechanisms of ASR-induced cracking at the material scale [5, 22–27]. This method is a  
159 powerful tool to model macroscopic expansion and analyze the progression of expansion  
160 cracks with ASR evolution. Mesoscale discrete models can evaluate the impact of aggregates



161 (such as distribution, size, and arrangement), the mechanical interaction between aggregate  
162 particles, and the distribution of expansive sites in the aggregate on ASR. Mesoscale modeling  
163 has been used to reproduce the crack propagation process generated by gel pockets in  
164 aggregate particles [5] according to aggregate size [22], stress effect [23], and the impact of  
165 creep on ASR expansion [24]. Three-dimensional aggregate particles were modeled with 3D-  
166 RBSM to reproduce the crack propagation in the mortar phase between aggregate particles  
167 during ASR [26]. In that work, an expansion strain was applied to the boundary between the  
168 aggregate and mortar phases. This assumption is representative of certain highly reactive  
169 particles. For most moderate or slowly reactive aggregates, cracks were observed inside  
170 aggregate particles [6, 7, 11]. The effect of the distribution of reactive sites in the aggregate  
171 can impact crack propagation during ASR, and therefore, it must be analyzed via mesoscale  
172 modeling.

173

#### 174 **2.4 Objectives of the analytical approach**

175 As described in the literature review, the crack pattern varies according to the type of  
176 reactive rock and expansive site distribution in the aggregate. This difference is attributable to  
177 the location of the origins of expansion in aggregates and to the speed of the flow of alkalis in  
178 reaching these different locations [21]. The distributions of ASR-crack patterns in concrete and  
179 aggregate have significant consequences on the damage induced by ASR at the structural  
180 scale.

181 The first objective of this work is to use a mesoscale model to evaluate the capacity of  
182 ASR mechanisms (gel pocket and reaction rim models) to reproduce the crack patterns, as  
183 both models are individually described in the literature. The relationship between the

184 macroscopic ASR expansion and internal damage of the aggregate and paste is often  
185 questioned in the literature. The nature of the aggregate and the distribution of reactive sites is  
186 considered responsible for the difference in damage observed in the literature for equal levels  
187 of ASR expansion.

188         The second objective of this work is to compare the crack patterns obtained for different  
189 expansion levels by mesoscale modeling with experimental observations from the literature.  
190 The crack patterns obtained by mesoscale modeling under different assumptions can help  
191 understand this issue.

192         In this study, the influence of the distribution of expansive sites on the cracking process  
193 was investigated from a mechanical point of view using a mesoscale discrete model. As the  
194 expansion progresses, the influence of the change in the physical properties of the ASR gel in  
195 cracks corresponding to the substitutional reaction between Na and Ca becomes more  
196 important. The inherent time-dependent behavior such as the creep of cementitious material  
197 becomes more pronounced with an increase in induced stress. In the early stage expansion,  
198 the ASR gel is well confined by the surrounding minerals or reaction rim. After cracking, the  
199 expansion behavior differs from the early stage because the ASR gel tends to flow without  
200 exerting expansive pressure when free space is available. At this stage, the stress generated  
201 by the rheological behavior of the ASR gel is significantly lower than the mechanical  
202 confinement stress, and the change in the physical properties of the ASR gel in cracks has a  
203 negligible effect on the initiation of the cracking process. In terms of creep, aggregate cracking  
204 is not considerably affected for typical reactive rocks because most of these rocks have  
205 negligible time-dependent behavior. In this study, the authors assessed the crack propagation

206 process in the early stage of expansion caused by the different distribution of the expansive  
207 sites in the absence of those influences.

208

### 209 **3. Mesoscopic Modeling Approach**

210 In this study, a mesoscale discrete model that expressly represents concrete material  
211 by aggregate particles and a mortar phase using a 3D-Rigid Body Spring Model was developed  
212 to analyze the ASR cracking process inside aggregates and between adjacent aggregates  
213 because of varying distributions of expansive sites in the aggregate. The 3D-RBSM allows  
214 mesoscale structural analysis and a powerful tool for comprehending the phenomena related  
215 to cracks as it can explicitly evaluate crack width and distribution [28]. The author has  
216 previously developed a 3D-RBSM for investigating the mechanism of concrete failure and  
217 deterioration involved in cracking such as in the shear failure of RC members [29], rebar  
218 corrosion [30, 31], drying shrinkage [32], and external sulfate attack [33]. In this section, an  
219 overview of the 3D-RBSM and ASR expansion model using the multi-aggregate model is  
220 presented.

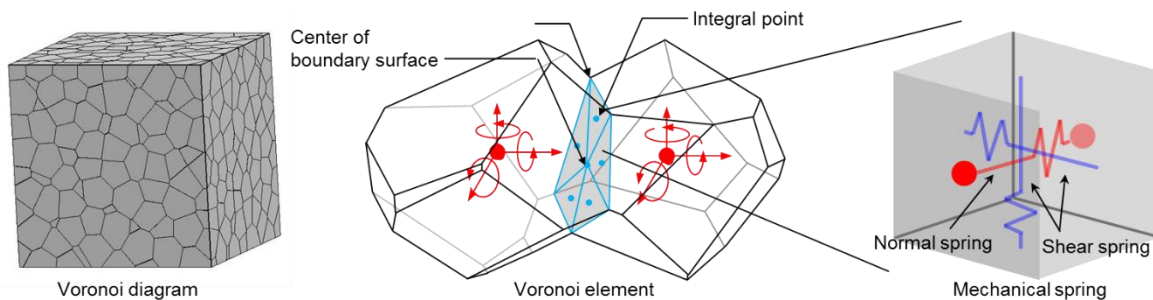
221

#### 222 **3.1 3D-Rigid Body Spring Model (3D-RBSM)**

223 The RBSM is a discrete model proposed by Kawai [28] and it is used for describing  
224 cracks. The RBSM is composed of rigid body elements with mechanical springs, which  
225 represent nonlinear constitutive laws of cementitious materials placed at the boundary surface  
226 between rigid body elements. The rigid body elements are discretized using random Voronoi  
227 particles to reduce element size dependency [34] as shown in Figure 1. A mesoscale material  
228 constitutive law corresponding to the element size is introduced to mechanical springs so that

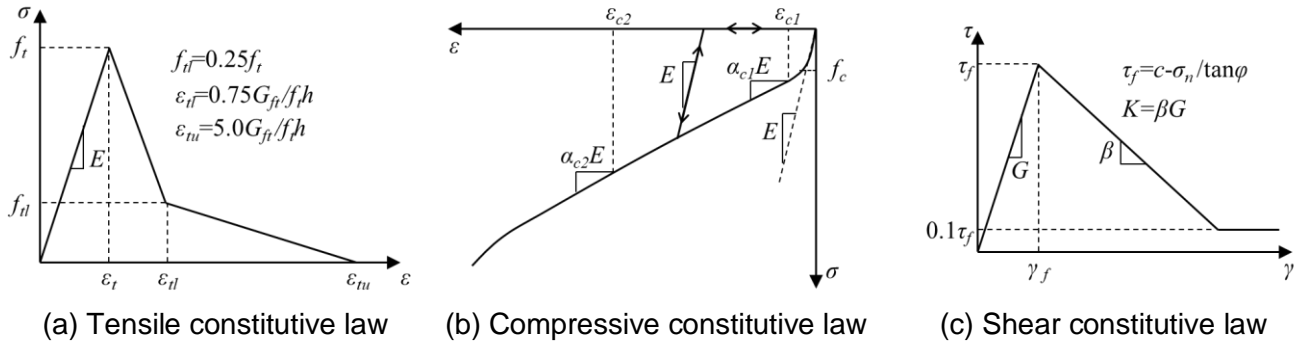
229 macroscopic mechanical behaviors are reproduced where the mechanical springs are  
 230 comprised of one normal spring and two shear springs arranged at integral points on the  
 231 boundary surface. Figure 2 shows the tensile, compressive, and shear constitutive laws [8].  
 232 The strain of the normal spring is defined as a change in the distance between the center of  
 233 gravity of adjacent elements with the normal spring behavior corresponding to this strain based  
 234 on tensile and compressive constitutive laws. For the tensile constitutive law (Figure 2 (a)), the  
 235 normal spring behaves linearly based on the elastic modulus  $E$  until reaching the tensile  
 236 strength with tensile softening behavior defined by the quarter model. As per the compressive  
 237 constitutive law shown in Figure 2 (b), the nonlinear behavior is described by a quadratic  
 238 function so that material failure is attributed to only tensile or shear failure. The shear  
 239 constitutive law shown in Figure 2 (c) is defined by the shear strain given by the two shear  
 240 springs. The shear springs behave linearly based on their shear stiffness  $G$  until they reach  
 241 their shear strength after which shear softening behavior is incorporated with the shear  
 242 softening coefficient  $K$  until  $0.1\tau_f$ . The shear softening coefficient  $K$  is obtained by the product  
 243 of the shear stiffness  $G$  and softening coefficient  $\beta$ . In addition, shear strength is applied by a  
 244 Mohr–Coulomb type criterion to consider the stress dependency of the normal spring. The  
 245 mesoscale parameters for the mesoscale constitutive law introduced to the normal and shear  
 246 springs are listed in Table 1. Details on the model are provided in [8].

247



248

249 Figure 1 Principle components of the 3D-RBSM: Voronoi elements and the normal and shear springs.  
 250



251  
 252

253  
 254

Figure 2 Mesoscale constitutive models for the normal and shear springs.

255 Table 1 Mesoscale parameters for the mesoscale constitutive law for the normal and shear springs [8].

NORMAL SPRING							
Elastic modulus	Tensile constitutive law		Compressive constitutive law				
	$\sigma_t$ (MPa)	$g_f$ (N/mm)	$f'_c$ (MPa)	$\epsilon_{c1}$	$\epsilon_{c2}$	$\alpha_{c1}$	$\alpha_{c2}$
$1.4 E^*$	$0.8 f_t^*$	$0.5 G_f^*$	$1.5 f'_c^*$	$\frac{-2\sigma_c}{E(1+\alpha_{c1})}$	-0.015	0.15	0.25

SHEAR SPRING							
Shear stiffness	Mohr–Coulomb fracture criteria			Softening coefficient			
	$c$ (MPa)	$\varphi$	$\sigma_b$ (MPa)	$\beta_0$	$\beta_{max}$	$X$	$K$
$\eta = G/E$	$0.14 f'_c^*$	37	$f'_c^*$	-0.05	-0.02	-0.01	-0.3

\* indicates macroscopic mechanical properties.

256

### 257 3.2 Aggregate model

258 In this study, two models are used for the aggregate as shown in Figure 3: single and  
 259 the multi-aggregate models.

#### 260 3.2.1 Single aggregate model

261 In the single aggregate model, one aggregate is arranged at the center of the analytical  
 262 model. This model is used to determine the change in cracking behavior inside the aggregate

263 precisely because of the varying expansive site distributions in the aggregate. The concrete  
264 model comprises the aggregate particles and mortar surrounding the aggregates with the  
265 analytical model in this case being cubic with a size of 40 × 40 × 40 mm and a 20-mm diameter  
266 aggregate placed at the center of the model. The average aggregate element size was 1 mm  
267 and the maximum element size for the mortar was 2 mm.

268

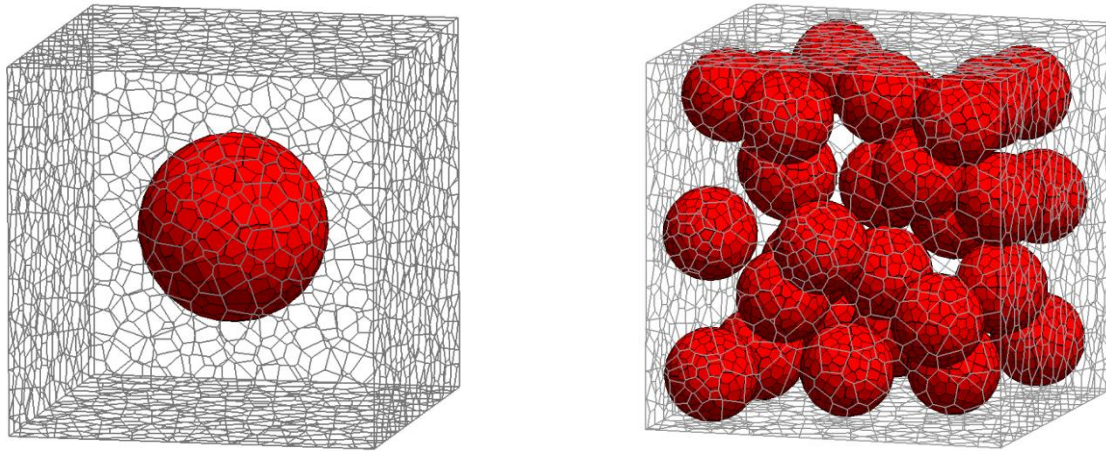
### 269 **3.2.2 Multi-aggregate model**

270 The multi-aggregate model represents multiple aggregates randomly arranged in the  
271 analytical model. This model verifies the crack propagation between adjacent aggregates for  
272 varying expansive site distributions. The comparison between single and multi-aggregate  
273 models leads to important conclusions on the interest in precisely modeling the distribution of  
274 aggregates in concrete to improve the evaluation of ASR expansion and the resulting cracking  
275 pattern. The analytical model is a cube with a size of 80 × 80 × 80 mm and 30 aggregates, with  
276 diameters of 20 mm, placed randomly in the analytical model. The average element size of the  
277 aggregate was 1 mm and the maximum mortar element size was 4 mm. In particular, at least  
278 two mortar elements are placed between adjacent aggregates to model crack propagation  
279 accurately.

280

### 281 **3.2.3 Analysis with proposed models**

282 For two aggregate models, three types of analytical meshes are constructed to assess  
283 the variation in expansion behavior because of differences in the arrangement of aggregate  
284 and expansive sites. Material parameters for the aggregate phase, mortar phase, and ITZ  
285 between these two phases are drawn from the literature and are listed in Table 2.



(a) Single aggregate model

(b) Multi-aggregate model

Figure 3 Aggregate models in the concrete.

Table 2 Material properties for the mortar and aggregate.

Scale	Material	$f_c'$ (MPa)	$E$ (GPa)	$f_t$ (MPa)	$c$ (MPa)	$G_f$ (Nm)
Macro	Aggregate <sup>*1</sup>	100.0	50.0	11.00	-	-
	Mortar <sup>*2</sup>	35.0	29.5	2.46	-	0.0559
Meso	Aggregate <sup>*3</sup>	150.0	70.0	8.80	14.0	0.0005 <sup>*4</sup>
	Mortar <sup>*3</sup>	52.5	41.3	1.97	4.9	0.0280
	ITZ <sup>*5</sup>	26.25	20.65	0.98	2.45	0.0140

\*1 Material properties for aggregate were based on [5] and [26].  $f_c'$  for the aggregate was assumed as 100 MPa.

\*2 The compressive strength of the mortar was set to 35 MPa and the other material properties of the mortar were calculated based on the formulation from the JSCE [35].

\*3 Mesoscale parameters are applied to calculate the mesoscale constitutive law based on [35] as listed in Table 1.

\*4 Fracture energy is unknown. In this analysis, it was applied using a small value as the aggregate cannot represent softening after cracking.

\*5 The properties of the ITZ are unknown. This analysis halved the mortar properties, similar to Wang's approach in [26].

292

### 293 3.3 Expansion model

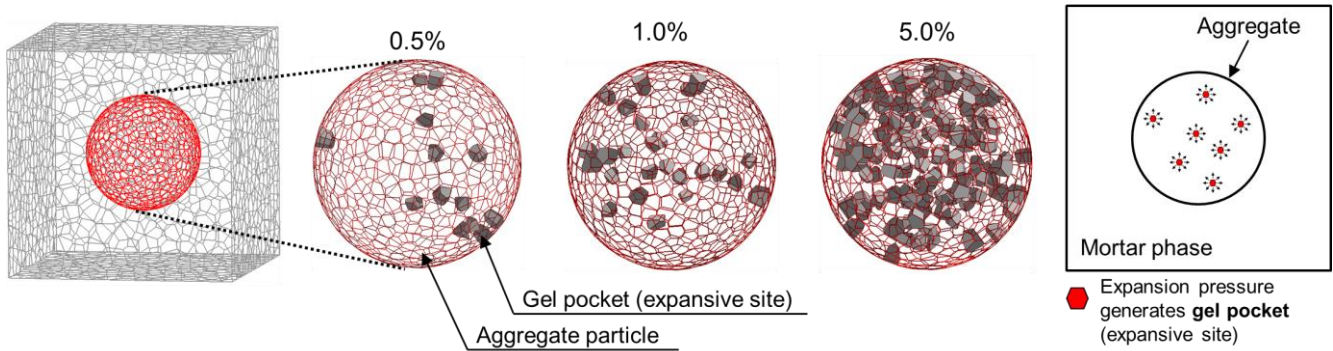
294 Expansion models used in this analysis are the gel pocket model proposed by Dunant  
 295 et al. [5] and the reaction rim model proposed by Ichikawa et al. [4]. Physicochemical  
 296 mechanisms were not considered in this work with the locations of ASR gel expansion  
 297 (expansive sites) corresponding to the reaction sites even after cracking. Thus, expansive sites  
 298 are assumed equal to the initial reaction sites.

299

### 300 3.3.1 Gel pocket model

301 For the gel pocket model, elements containing expansive sites are randomly selected in  
 302 the aggregate elements assumed to be the microstructural origin of the expansion. Three  
 303 expansive site ratios in the entire aggregate elements were studied to analyze the effect of the  
 304 number of aggregate expansive sites on ASR expansion and the cracking mechanisms: 0.5%,  
 305 1.0%, and 5.0%. In particular, the aggregate elements containing the expansive sites were  
 306 randomly selected up to the corresponding volume percentages of all aggregate elements.  
 307 Thus, the number of expansive sites was decided by the expansive site ratios and the  
 308 distribution of the expansive sites. The analytical models for the single aggregate model for  
 309 each expansive site ratio are shown in Figure 4. The expansive site distribution in an aggregate  
 310 can be randomly arranged (Figure 4, where the visualized expansive site for 5% of the  
 311 aggregate volume seems to be higher in the plane caused by the visualization problem).

312



313

314

Figure 4 Single aggregate model for the gel pocket model.

315

### 316 3.3.2 Reaction rim model

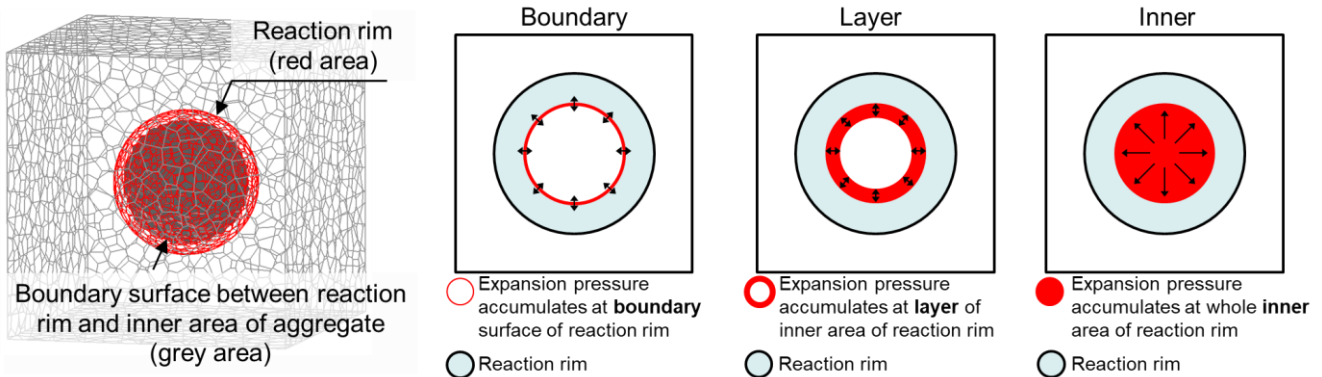


317 For the reaction rim model, the expansive sites are considered to form at the inner area  
 318 of the reaction rim. The location of the expansion pressure inside the aggregate has not been  
 319 clarified in the literature. Therefore, three types of expansion models were constructed, as  
 320 shown in Figure 5.

- 321 - Boundary model: The thin expansive sites are localized at the inner surface between the  
 322 reaction rim and the center of the aggregate.
- 323 - Layer model: The expansive sites are localized in a thick layer between the reaction rim  
 324 and the center of the aggregate with a thickness of 2 mm.
- 325 - Inner model: The expansive sites uniformly accumulate over the entire inner area of the  
 326 reaction rim.

327 The change in the elastic modulus caused by the densification of surface layers owing  
 328 to rim formation and the change in the thickness of the reaction rim with time were not  
 329 considered in this model. The thickness of the reaction rim was assumed to be 2 mm based on  
 330 Ichikawa et al. [4], and it was maintained at 2 mm in all models in this study. Prior to the present  
 331 study, it was confirmed with a sensitivity analysis that the effect of the thickness of the reaction  
 332 rim has a slight effect on the crack pattern.

333



335 (a) Aggregate model

(b) Boundary model

(c) Layer model

(d) Inner model

336 Figure 5 Single aggregate model for the reaction rim model: (a) Aggregate model where the surface  
337 area is the 2-mm-thick reaction rim and the inner area has an expansibility with different expansive  
338 sites; (b) boundary model with thin expansive sites localized at the inner surface between the reaction  
339 rim and aggregate center; (c) layer model with expansive sites localized in a thick layer between the  
340 reaction rim and aggregate center with a thickness of 2 mm; and (d) inner model where expansion sites  
341 uniformly accumulate at the entire inner area of the reaction rim.

342

### 343 **3.3.3 Numerical description of the expansive site for the multi-aggregate model**

344 Figure 6 shows the analytical model of the multi-aggregate model for the gel pocket  
345 model and reaction rim model with the numerical description used to describe the expansive  
346 sites listed in Table 3. The arrangement of the aggregates used for the gel pocket model and  
347 the boundary model of the reaction rim model were the same, whereas the arrangement for  
348 the layer and inner models varied from those of the other models. This is because the layer  
349 and inner models required a spherical volumetric element arrangement in the aggregate.  
350 However, it was confirmed that the influence of different aggregate locations in the analytical  
351 model on the expansion behavior is negligible for the multi-aggregate model.

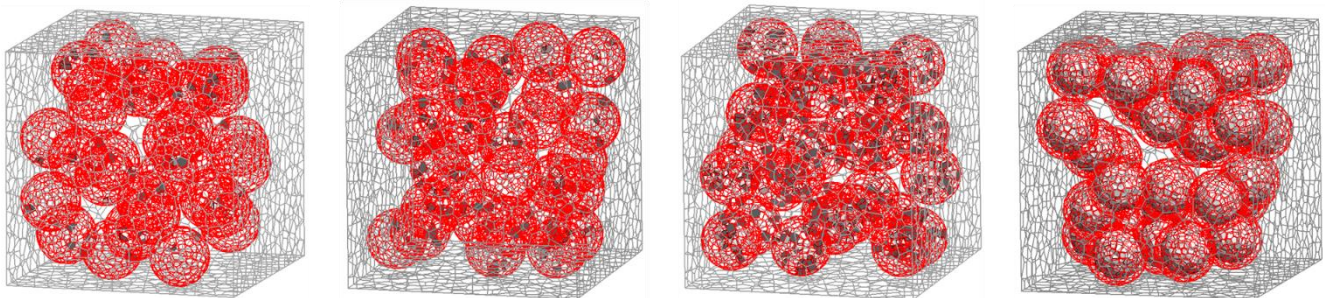
352 Regarding the gel pocket model, the expansive site ratio of the aggregate is the same  
353 as that of the single aggregate model. Then, to assess the expansive site distribution of the gel  
354 pocket model quantitatively, the average volume corresponding to the expansive site and the  
355 average spacing between adjacent expansive sites were calculated as listed in Table 3. The  
356 average volume corresponding to the expansive site was derived from the aggregate volume  
357 divided by the expansive site element number. For spheres centered on one element of the  
358 expansive site with diameters equal to the distance to the closest “expansive site”, the mean  
359 sphere diameter was calculated as the average diameter for all expansive sites, thereby giving  
360 the average spacing between adjacent expansive sites. According to the expansive site  
361 distribution, the average spacing between adjacent expansive sites for expansive site ratios of

362 0.5, 1.0, and 5.0% are 6.44 mm, 5.22 mm, and 3.12 mm, respectively. Table 3 summarizes the  
363 details on how the expansive sites are densely distributed in the aggregate. However, these  
364 values are only averages, and they are one of the indices to represent the expansive site  
365 distribution.

366 For the reaction rim model, the expansive site volume ratios of the aggregate for the  
367 layer and inner models are 42.17% and 43.56 %, respectively, while the boundary model has  
368 no expansive site volume as the expansive site is applied to the boundary surface. These high  
369 values of expansive sites are imposed by the geometry of the rim (radius and thickness). In  
370 comparison to the gel pocket model, the ratios of the expansive site for the aggregate for the  
371 layer and inner models are considerably higher than that of the gel pocket model (between  
372 0.5% and 5.0%). The consequences of the difference in terms of macroscopic expansion and  
373 cracking are discussed in Section 4.2.2.

374 For both expansion models, an expansion strain of  $100 \mu\text{m}/\text{m}$  was constantly applied to  
375 the normal spring of the expansive site as imposed strains (so-called initial strain in the field of  
376 computational dynamics), and it was applied to the single aggregate model. This analytical  
377 method for applying the expansion strain is similar to that reported by Wang et al. [26]. As the  
378 expansion rate is equal, earlier expansion results for models with the greatest expansive site  
379 volume. The viscoelastic behavior of ASR gel will be modeled in future research.

380



381

382 (a) 0.5% (b) 1.0% (d) 5.0% (d) Reaction rim model  
 383 Figure 6 Multi-aggregate model for the gel pocket model and reaction rim model; (a), (b), and (c) are  
 384 the gel pocket model for each expansive site ratio, and (d) is the reaction rim model (three assumptions  
 385 for the expansive site inside the aggregate as described in Figure 5 are analyzed for the multi-aggregate  
 386 model).

387  
 388 Table 3 Expansive site details for the multi-aggregate model.

Expansion model	Gel pocket model			Reaction rim model		
	0.5%	1.0%	5.0%	Boundary	Layer	Inner
Total element number		18,064			18,075	18,130
Total volume (mm <sup>3</sup> )			512,000			
Aggregate element number		9,559			9,530	9,598
Aggregate Volume (mm <sup>3</sup> )		127,768			127,761	127,758
Expansive site element number	52	98	457	-	3,030	3,486
Expansive site volume (mm <sup>3</sup> )	709	1,320	5,995	-	53,872	55,653
Vol.% in aggregate	0.56	1.03	4.69	-	42.17	43.56
Average volume of expansive site <sup>*1</sup> (mm <sup>3</sup> )	2,457.1	1,303.8	279.6	-	-	-
Average spacing of adjacent expansive site <sup>*2</sup> (mm)	6.44	5.22	3.12	-	-	-

\*1: Average volume of the origin of expansion = aggregate volume / expansive site element number.

\*2: Average spacing of adjacent expansive sites is the sphere diameter calculated by average volume of the expansive site.

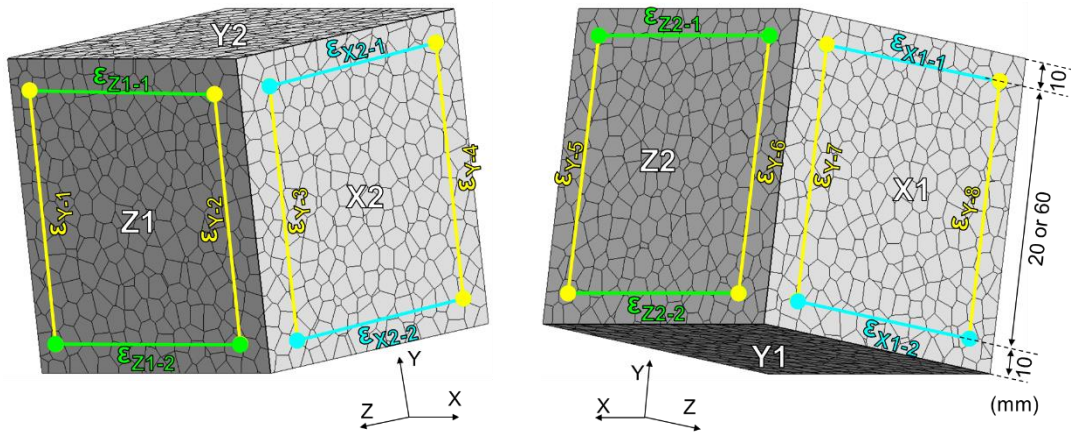
389

### 390 3.4 Definition of macroscopic expansion strain

391 In this analysis, the macroscopic expansions in the x-, y-, and z-directions were defined  
 392 as shown in Figure 7. The macroscopic expansion is the concrete strain, which is the  
 393 consequence of the cumulative strain applied to the reactive sites. Macroscopic expansion is  
 394 determined by the model. Four gauge points were placed at four surfaces in the x- and z-  
 395 directions, and each gauge point was placed at the element where these elements were 10  
 396 mm from the nearest vertex of the surface; the gauge lengths were approximately 20 mm. Two  
 397 lateral macroscopic expansions in the y-direction and two transversal macroscopic expansions  
 398 in the x- and z-directions were defined from the four gauge points of each surface. Therefore,  
 399 there are eight lateral macroscopic expansions and four transversal macroscopic expansions

400 in the  $x$ - and  $z$ -directions. Thus, the average strain in each direction, lateral macroscopic  
 401 expansion in the  $y$ -direction, and transversal macroscopic expansion in the  $x$ - and  $z$ -directions  
 402 can be obtained. The volumetric strain was defined as the summation of the lateral and two  
 403 transversal macroscopic expansions.

404



405

406

Figure 7 Definition of macroscopic expansion.

407

## 408 4. Numerical Simulations and Results

### 409 4.1 Analytical results for the single aggregate model

410 The change in expansion behavior caused by the different distributions of the expansive  
 411 site based on the gel pocket and reaction rim models was first verified with the single aggregate  
 412 model. The process of expansion crack propagation is discussed according to the expansion  
 413 evolution, deformation, crack distribution, horizontal tensile and vertical compressive stress  
 414 distributions at the center of the cross-sectional area, which are shown in Figures 8–13. In  
 415 these figures, the expansion process is indicated by the cumulative applied strain of the  
 416 expansive sites. The cumulative applied strain is calculated by accumulating the applied strain  
 417 at one expansive site for each step. For instance, after one-hundred calculation steps, the

418 resulting cumulative applied strain is 1.0 % when the applied strain is 100  $\mu\text{m}/\text{m}$  (0.01%) for  
419 every step.

420

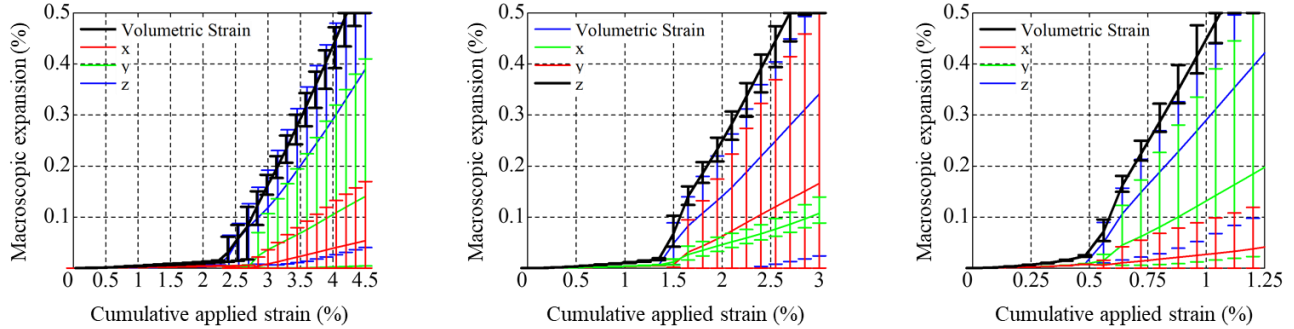
#### 421 **4.1.1 Gel pocket model**

422 The expansion evolution until the volumetric strain is reached is approximately 0.5% as  
423 shown in Figure 8. The cumulative applied strain in the expansive site necessary to reach 0.5%  
424 of volumetric expansion in the concrete decreases as the ratio of the expansive site increases  
425 (i.e., the cumulative applied strain has to be lower as the expansive site is greater). The  
426 expansion in the three coordinate directions demonstrates high anisotropy according to the  
427 expansive site distribution; this expansion occurs in one direction and the expansion in the two  
428 other directions is close to zero. Thus, the crack propagated in only one direction (Figure 9).  
429 This leads to high scattering in the results for directional expansions according to expansive  
430 site distribution, while the volumetric strain has only small differences. Therefore, the  
431 macroscopic expansion change is considerably constant and the only weakly dependent on  
432 the direction of the expansion crack propagation. The macroscopic expansion in the three  
433 directions varied widely as a result of the variation in crack propagation direction because of  
434 the analytical mesh and arrangement of the expansive sites. In the case of the single aggregate  
435 model used for the gel pocket model, once one crack is initiated in one direction, the increase  
436 in cumulative applied strain leads to this crack opening without the initiation of new cracks in  
437 the other directions.

438 This has already been observed for macro-modeling when perfect plasticity is used to  
439 represent ASR expansion. In the case of macro-modeling, this phenomenon has been solved  
440 by the addition of a hardening behavior to plasticity induced by ASR expansion [36]. With a

441 hardening law, the ASR expansion is isotropic under stress-free conditions [37].

442



443

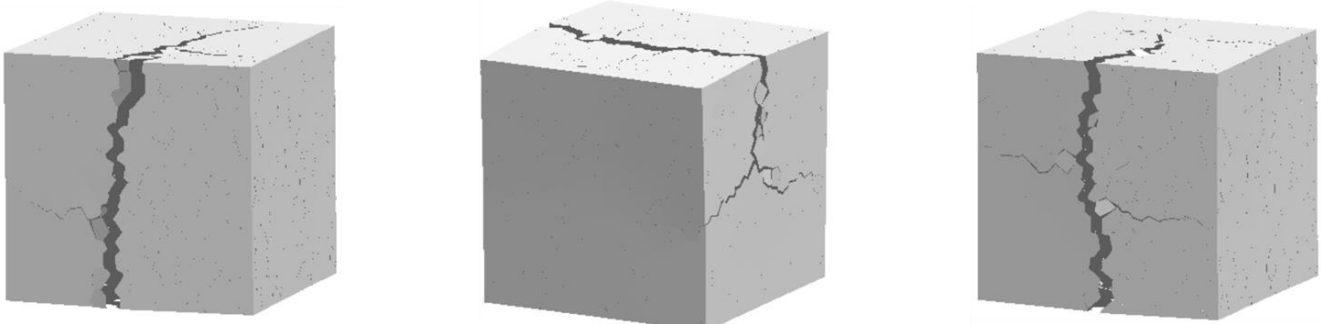
444 (a) 0.5%

444 (b) 1.0%

444 (c) 5.0%

445 Figure 8 Concrete expansion evolution with cumulative applied strain of the expansive sites for the gel  
446 pocket model for the single aggregate model until a volumetric strain of approximately 0.5% is reached.  
447 The error bars are calculated from the three different analytical meshes.

448



449

450 (a) 0.5%

450 (b) 1.0%

450 (c) 5.0%

451 Figure 9 Deformation of the gel pocket model for the single aggregate model when the volumetric strain  
452 reaches approximately 0.5% (magnification is ten times).

453

454 Figure 10 presents the crack distribution and horizontal tensile and vertical compressive  
455 stresses at the center of the cross-sectional area. Four stages were extracted for the analysis:  
456 before cracking, at the generation of crack, after crack propagation, and at approximately 0.5%  
457 of the volumetric strain. According to the crack distribution, when the expansive site ratio is  
458 lower than 1%, first, cracks are generated inside the aggregate, and subsequently, the cracks

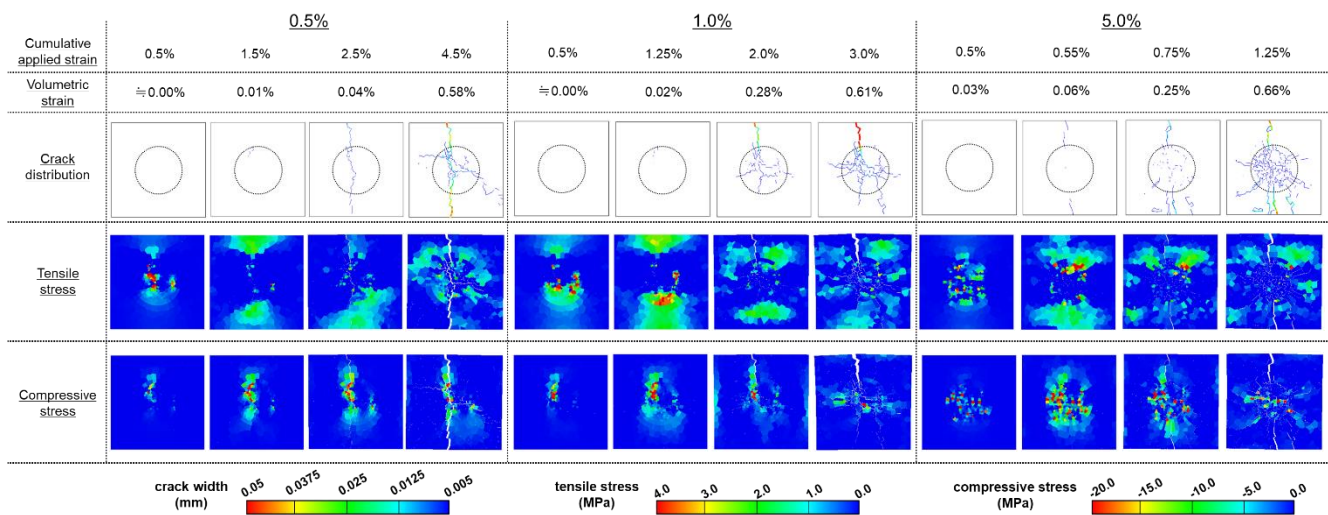
459 propagate from the mortar to the aggregate. In the case of an expansive site ratio of 5%, the  
460 cracks inside the aggregate are finer and fewer, and crack propagation from the mortar to the  
461 aggregate occurs at almost the same time. Compressive stresses are generated locally in the  
462 expansive sites and they reduce slightly with crack propagation. Before cracking, the unstable  
463 stress balance causes localized tensile stress and leads to crack initiation. After cracking, crack  
464 propagation is influenced by tensile stress as the orientation of cracking is already determined  
465 at the time of initiation. In addition, after cracking, the stresses gradually release, thereby  
466 corresponding to crack development. Thus, the compressive stress cannot accumulate up to a  
467 higher stress level and affect crack propagation. Tensile stresses are generated close to the  
468 expansive site before cracking, and they gradually release as the cracks propagate inside the  
469 aggregate and from the mortar to the aggregate. In the case of an expansive site ratio of 5.0%,  
470 there are many expansive sites in the aggregate. Compressive stresses in the aggregate  
471 appear and increase because of confinement by the cement paste unless local compression  
472 failure occurs. During this stress state in the aggregate, the tensile stresses transfer from the  
473 aggregate to the mortar, and the tensile stresses at the outer surface reach the tensile strength.  
474 Thus, aggregate cracking and cracks propagating from the mortar to the aggregate occur  
475 almost simultaneously.

476         The mechanism behind the unexpected cracking process from the mortar to the  
477 aggregate is discussed as follows. First, compressive stresses generated at the expansive  
478 sites as the surrounding “nonreactive” aggregate phases inhibit the deformation because of  
479 expansion. Simultaneously, tensile stresses are generated at the surrounding aggregate  
480 phases corresponding to the generation of compressive stresses, and the internal stresses  
481 then become balanced. Further, as the compressive stresses in the expansive sites develop,



482 the surrounding tensile stresses develop and gradually transfer to the external surface.  
 483 Because of the effect of three-dimensional internal constraints at the inner area, the tensile  
 484 stresses are difficult to develop though small amounts of damage could be generated. The  
 485 tensile stresses outside the mortar phase can increase up to the tensile strength as the effect  
 486 of the internal constraint is smaller or almost zero at the outer surface of the mortar phase as  
 487 compared to the inner surface. This is why cracks propagating from the mortar to the aggregate  
 488 can appear, and it should be noted that this crack observed in the single aggregate model is  
 489 an evident result from the analytical approach. Considering the actual heterogeneity of the  
 490 aggregate and its shape, stress concentrations could be generated inside the real aggregate.  
 491 These stress concentrations could manifest as cracks because they promoted the localization  
 492 of the aggregate cracking and inhibited the uniform tensile stress transfer. Thus, the crack  
 493 propagating from the mortar to the aggregate—as obtained by the numerical approach—can  
 494 be explained by the internal constraint effect.

495 Numerical results using the gel pocket model confirmed that the crack pattern has sharp  
 496 cracks [11] and crack distributions when the expansive site ratio is lower than 1.0% are similar  
 497 to those of Dunant [5].



498

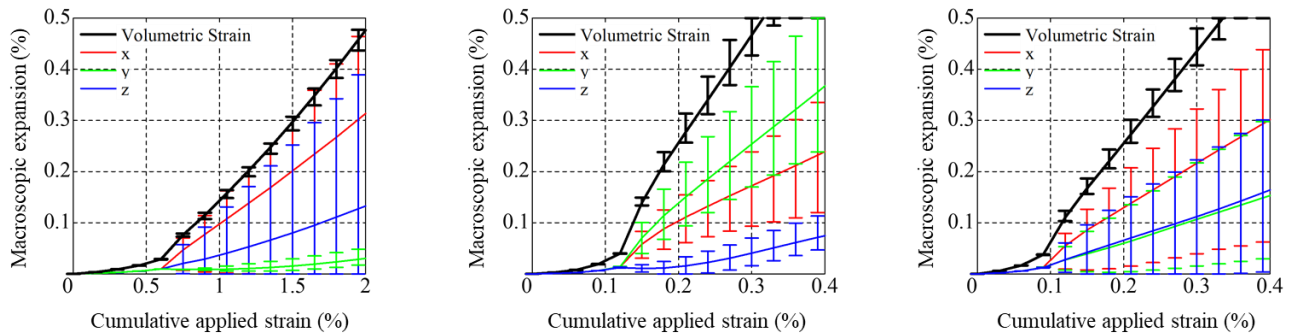
499 Figure 10 Crack distribution and horizontal tensile and vertical compressive stresses at the center of  
 500 the cross-sectional area of the gel pocket model for the single aggregate model (magnification of the  
 501 deformation is ten times). The black broken line indicates the boundary surface of the aggregate. The  
 502 four cumulative applied strain stages represent results before cracking, at the generation of cracking,  
 503 after crack propagation, and after the volumetric strain reaches 0.5%.

504

#### 505 4.1.2 Reaction rim model

506 The analytical results for the reaction rim model are shown in Figures 11–13. The  
 507 expansion evolution until the volumetric strain is approximately 0.5% is shown in Figure 11.  
 508 First, the effect of the assumption of the location of the pressure (boundary, layer, and inner  
 509 model) is discussed. The boundary model requires a higher cumulative applied strain to reach  
 510 0.5% of the volumetric strain, while the cumulative applied strains of the layer and inner  
 511 models are equal. The variation of the expansion in the three directions and volumetric strain for all  
 512 cases are similar to the gel pocket model. This is because the expansion cracks propagate in  
 513 one direction for the single aggregate model as shown in Figure 12.

514



515

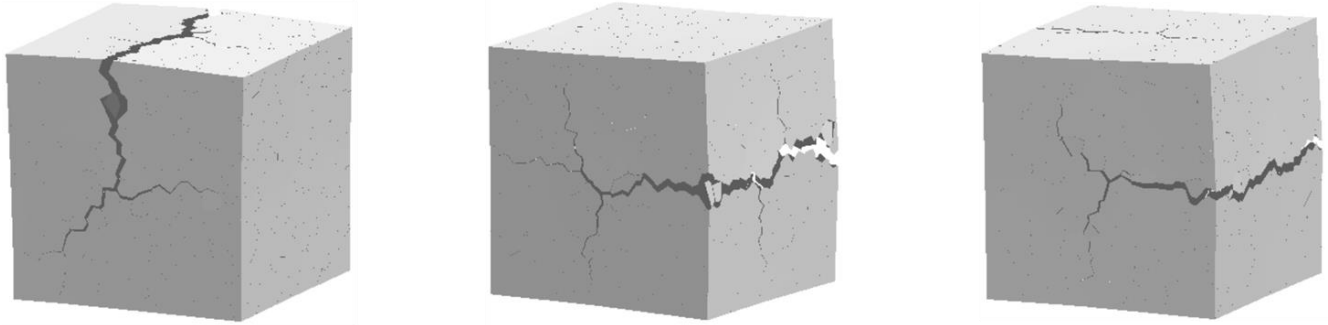
516 (a) Boundary model

(b) Layer model

(c) Inner model

517 Figure 11 Concrete expansion evolution versus cumulative applied strain of expansive sites for the  
 518 reaction rim model for the single aggregate model up to a volumetric strain of approximately 0.5%. The  
 519 error bars are calculated from three different analytical meshes.

520



521

522 (a) Boundary model

(b) Layer model

(c) Inner model

523 Figure 12 Deformation for the reaction rim model for the single aggregate model when the volumetric  
 524 strain reaches approximately 0.5% (magnification is ten times).

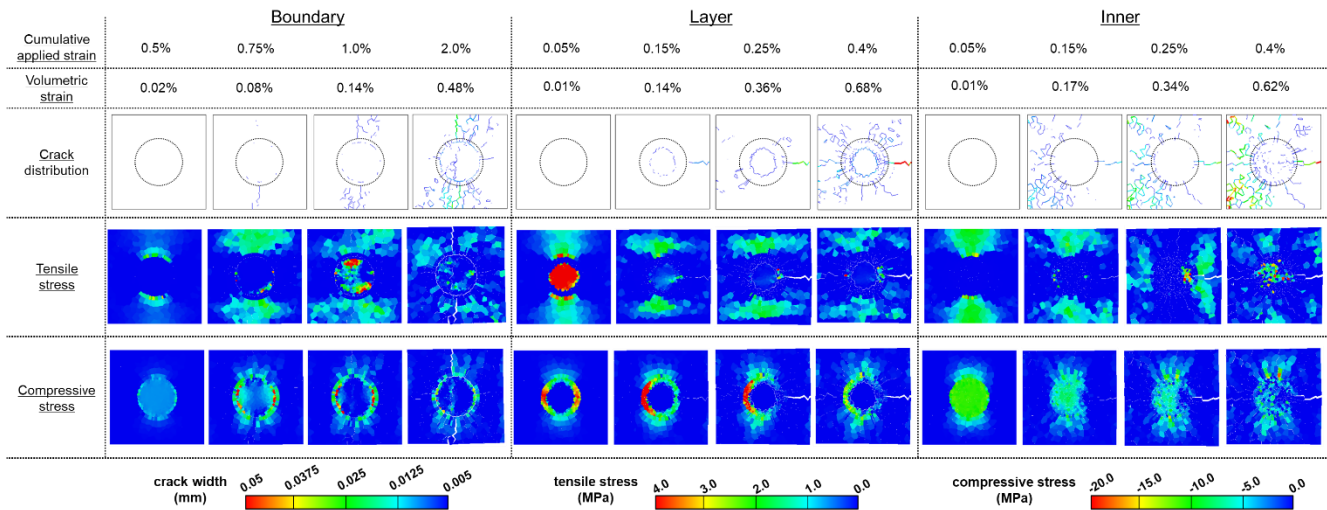
525

526 Figure 13 presents the crack distribution and tensile and compressive stresses at the  
 527 center of the cross-sectional area. In terms of the crack distribution inside the aggregate, cracks  
 528 are initiated in the aggregate along the surface for the boundary and layer models (ortho-radial  
 529 cracks in the aggregate), while the circumferential cracks in the aggregate cannot be observed  
 530 for the inner model before high expansion levels. Because the cumulative applied strain  
 531 increases, cracks passing through the aggregate are generated for the boundary model and  
 532 finer cracks are generated in expansive sites for the layer model with finer cracks distributed  
 533 throughout the aggregate area. In addition, cracks that propagate from the mortar to the  
 534 aggregate can be observed for all cases. The mechanism for the progress of these cracks is  
 535 the same as the gel pocket model described in Section 4.1.1. In terms of stress distribution,  
 536 the characteristic distribution caused by different expansive sites can be observed before  
 537 cracking. For the boundary and inner models, tensile stress is generated at the expansive sites  
 538 and propagates to the mortar, whereas compressive stress accumulates at the inner area of  
 539 the reaction rim. For the layer model, considerable levels of tensile stress are generated in the  
 540 inner area of the expansive layer. Further, tensile stress propagates outside the expansive  
 541 layer, whereas compressive stress is generated at the expansive layer. Therefore, the stress

542 state inside the aggregate before cracking can be changed because of different expansive sites.  
 543 This unique stress distribution will be vital in comprehending the origin of the expansion  
 544 pressure. With the accompanying crack development, the tensile and compressive stresses  
 545 are gradually released. The expansion crack propagation in only one direction is because of  
 546 the stress release corresponding to cracking.

547 Based on the analytical results of the reaction rim model, it can be confirmed that onion  
 548 skin cracking [11] appears with the boundary and layer models. For the boundary model, the  
 549 cracks passing through the aggregate appear when the volumetric strain reaches 0.5%.

550



551

552 Figure 13 Crack distribution and tensile and compressive stresses at the center of the cross-sectional  
 553 area of the reaction rim model for the single aggregate model (magnification of deformation is ten times).  
 554 The black broken line indicates the boundary surface of the aggregate. The four cumulative applied  
 555 strain stages represent results before cracking, at the generation of cracking, after crack propagation,  
 556 and after volumetric strain reaches approximately 0.5%.

557

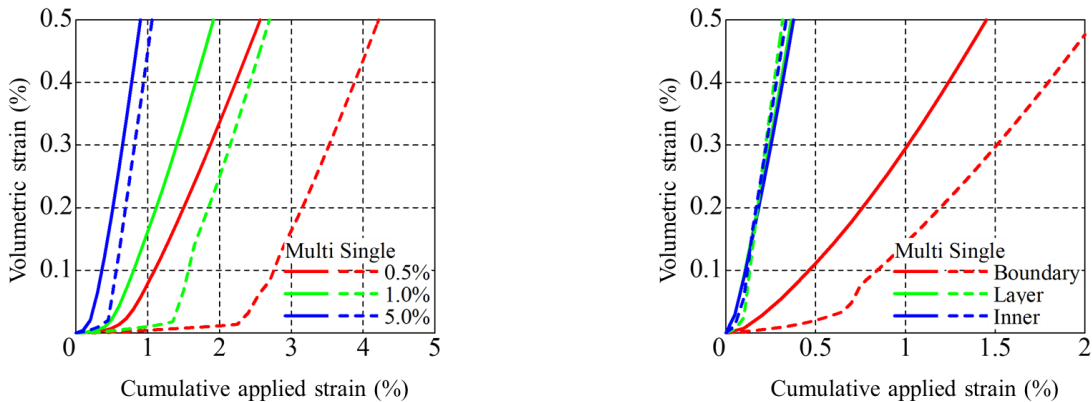
## 558 4.2 Analytical results of the multi-aggregate model

### 559 4.2.1 Comparison between the single aggregate and multi-aggregate models

560 The differences in volumetric evolution and crack distribution obtained with the single

561 aggregate and multi-aggregate models are compared based on the expansion level,  
562 deformation, and crack distributions at the center of their cross-sectional areas.

563 For the volumetric strain (Figure 14 (a)), expansions obtained with the gel pocket model  
564 for the multi-aggregate model are greater than those obtained with the single aggregate model.  
565 The difference between single and multi-aggregate models decreases with the increasing  
566 expansive site ratio. For a reaction rim model (Figure 14 (b)), the volumetric strain of the  
567 boundary model for the multi-aggregate model is greater than the expansion of the single  
568 aggregate model, whereas the volumetric strains of the other models are not affected by the  
569 number of reactive aggregates.



570

571 (a) Gel pocket model

571 (b) Reaction rim model

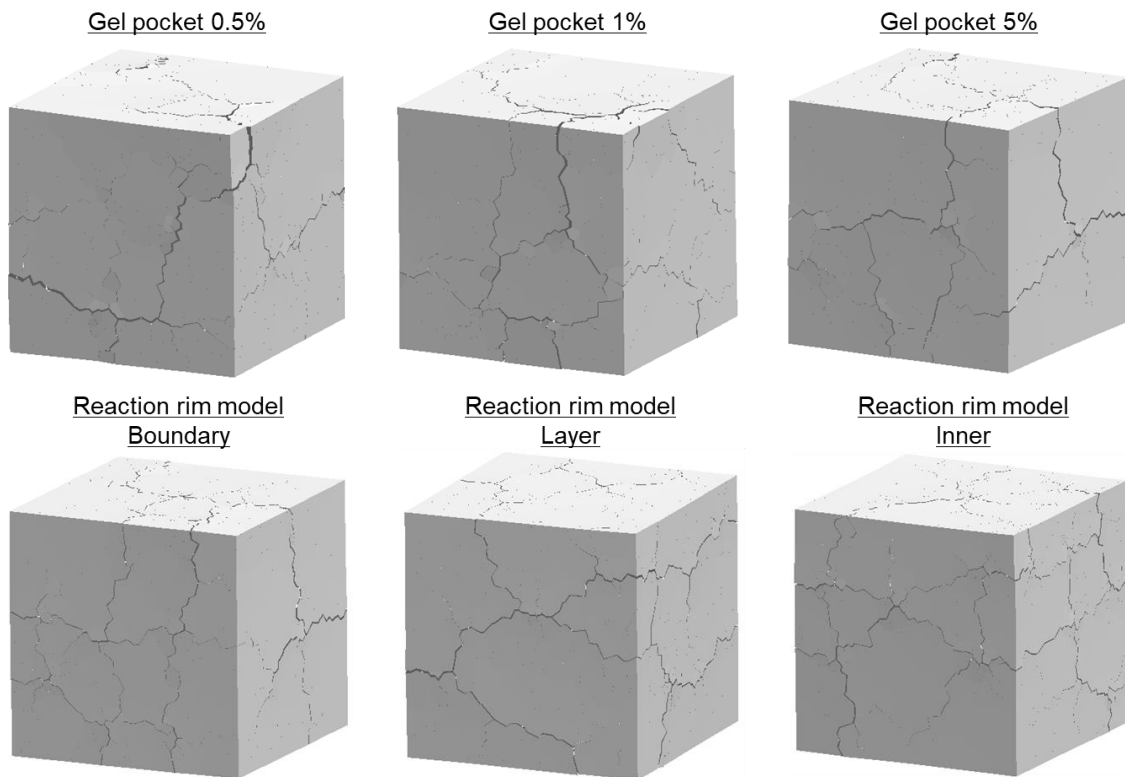
572 Figure 14 Comparison of volumetric strain evolution between the single aggregate and multi-aggregate  
573 models for both expansion models.

574

575 According to the surface crack distribution (Figures 9, 12, and 15), the superficial cracks  
576 of the multi-aggregate model are distributed in all directions, whereas the single aggregate  
577 model predicts cracks orientated in a single direction; this is because multiple aggregates are  
578 randomly arranged in space. The number of surface cracks in the gel pocket model increases  
579 with increasing expansive site ratio, while that of the reaction rim model is unaffected by the

580 difference in the expansive site ratio. The explanation for the difference between the single and  
581 multi-aggregate models is more pronounced for the gel pocket model as follows. The number  
582 of cracks is reduced when the expansive site ratio is smaller as the expansive sites are more  
583 localized. In the multi-aggregate model, cracks connected to adjacent aggregates can be  
584 observed. These cracks are generated because of the interaction of stresses between adjacent  
585 aggregates. Considering these features, the contribution of the cracks connecting adjacent  
586 aggregates becomes more pronounced when the expansive site ratio is less.

587



589

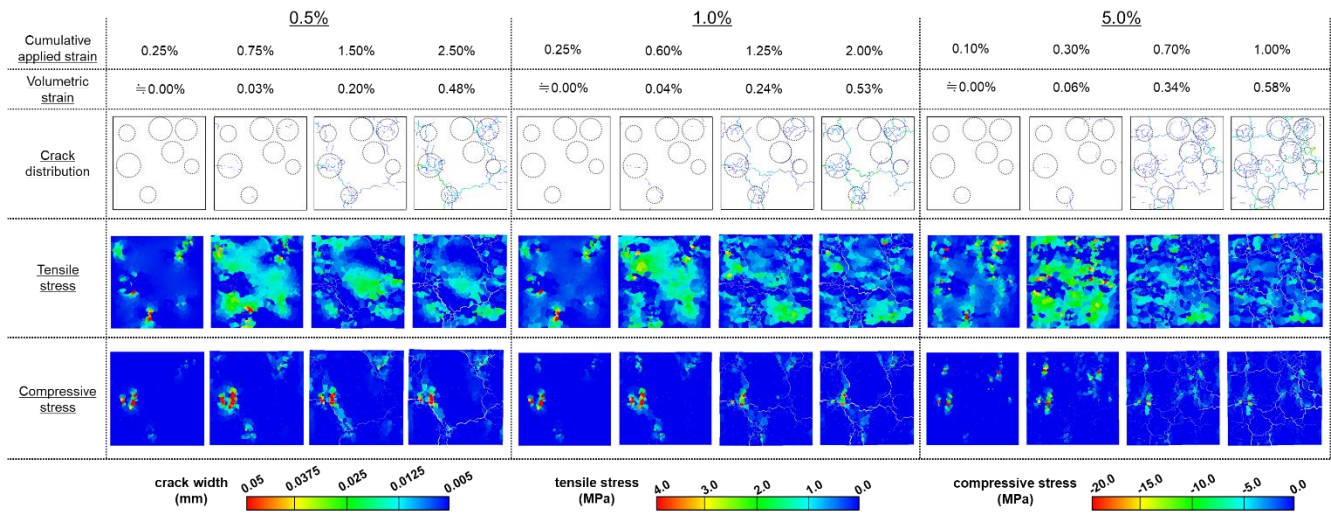
590 Figure 15 Deformation of the multi-aggregate model when the volumetric strain reaches approximately  
591 0.5% (magnification is five times).

592

593 In addition, with respect to the crack distribution at the center of the cross-sectional area  
594 (Figures 10, 13, and 16), the expansion cracks inside the aggregate for the multi-aggregate

595 model developed in the same manner as the single aggregate model. However, cracks  
 596 propagated between adjacent aggregates for the multi-aggregate model, whereas cracks  
 597 propagating from the mortar to the aggregate are observed for the single aggregate model.  
 598 According to the tensile and compressive stress distributions at the center of the cross-  
 599 sectional area (Figures 10, 13, and 16), the stress distribution is influenced by multiple  
 600 aggregates. Before cracking, the compressive stress distributions for all expansion models are  
 601 similar to those of the single aggregate model. The tensile stress is dispersed and propagates  
 602 in the mortar phase for the gel pocket model, whereas it propagates between adjacent  
 603 aggregates to become connected in the reaction rim model. This is caused by the random  
 604 arrangement of multiple aggregates. In particular, stresses decrease gradually, thereby  
 605 corresponding to the development of cracks between aggregates.

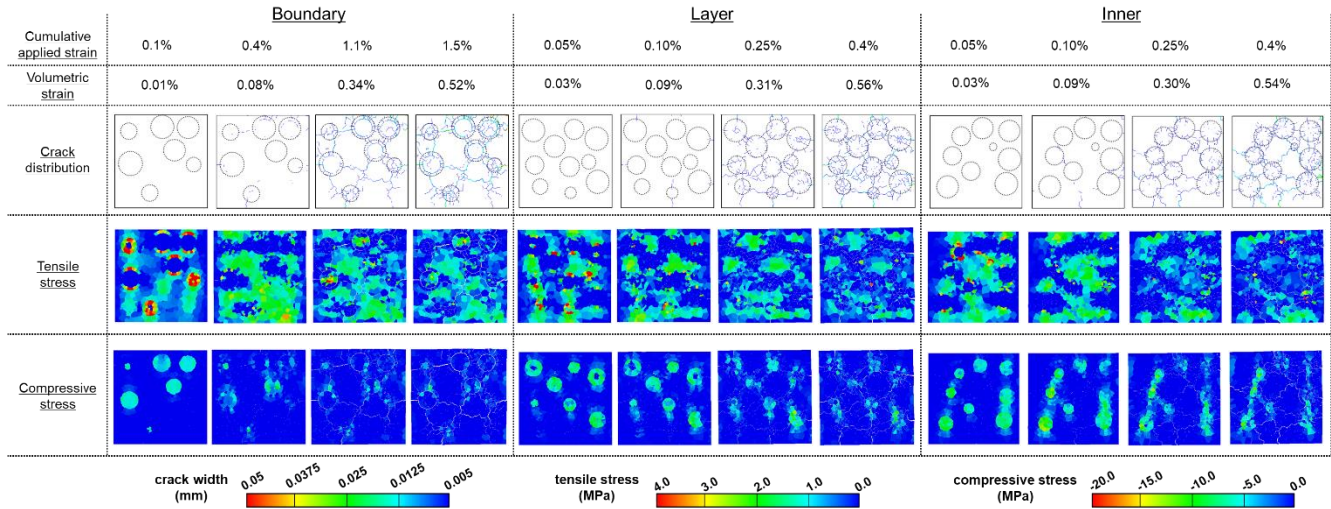
606



607

608

(a) Gel pocket model



609

610

(b) Reaction rim model

611 Figure 16 Crack distribution, and tensile and compressive stress distributions at the center of the cross-  
612 sectional area of the multi-aggregate model (magnification of deformation is ten times). The black  
613 broken line indicates the boundary surface of the aggregate. The four cumulative applied strain stages  
614 represent results before cracking, at the generation of cracking, after crack propagation, and after  
615 volumetric strain reaches approximately 0.5%.

616

617 Based on these analytical results, the volumetric strain developed because it was  
618 influenced only by the small expansive site ratio and the boundary model, which might be  
619 attributable to the occurrence of cracks between aggregates. The small expansive site ratio in  
620 the gel pocket and boundary models are likely to generate fewer cracks. Therefore, the effect  
621 of the occurrence of cracks between aggregates on volumetric strain development increases.  
622 From the comparison between the single and multi-aggregate models, it can be observed that  
623 for the multi-aggregate model, the cracks between adjacent aggregates can be generated and  
624 accompanied by cracks inside the aggregates. These cracks would accelerate volumetric strain  
625 development even if the expansive sites are identical. Thus, for the single aggregate model,  
626 cracks propagating from the mortar to the aggregate can appear as the stress transfers from  
627 the expansive site is not inhibited. For the multi-aggregate model, the stress is nonuniformly  
628 distributed because of adjacent aggregates and the cracks connecting them. Furthermore,



629 crack propagation from the expansive site in the aggregates into the mortar tends to be arrested  
630 by adjacent aggregates. Because of this interference of adjacent aggregates, the crack  
631 orientation changes and the macroscopic expansion becomes isotropic.

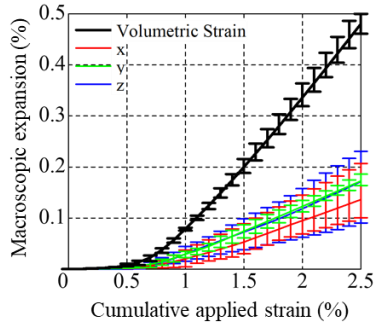
632

#### 633 **4.2.2 Effect of the distribution of the expansive sites within the aggregate on expansion**

634 The effect of the distribution of the expansive sites within the aggregate on the  
635 expansion behaviors is discussed based on the analytical results of the expansion evolution  
636 and crack volume (Figures 17–20). The expansion evolution (Figures 17 and 18) clearly  
637 indicates that the scattering of the expansion results obtained by the multi-aggregate model is  
638 less than that obtained by the single aggregate model. In the case of the gel pocket model, the  
639 range of the variation of expansion ranges from 0.15% to 0.20% at the maximum cumulative  
640 applied strain and the expansions in all directions change in the same manner; however, for  
641 the reaction rim model, the variation of expansion is very small and within 0.10%. Figures 17  
642 and 18 highlight the difference in the expansions obtained by the different models as the ratio  
643 of expansive sites is higher in the layer and inner models, and the applied strains have to be  
644 smaller to obtain the same macroscopic expansion. This study focuses on the mechanical  
645 aspects, and all expansive sites are supposed to be exerted on by the same expansion. In  
646 reality, the volume of expansive sites leading to the expansion depends on chemical conditions  
647 (alkali, water, calcium, etc.) and a large quantity of reactive silica cannot alone lead to a large  
648 expansion. The consequences of reactant supply to reactive silica should be considered in  
649 future research to obtain a comparable volume of expansive sites. In the following discussion,  
650 a comparison with literature is presented based on the cracking observations obtained for a  
651 particular level of macroscopic expansion; however, the volume of expansive sites necessary

652 to obtain the level of expansion is not considered in the comparison.

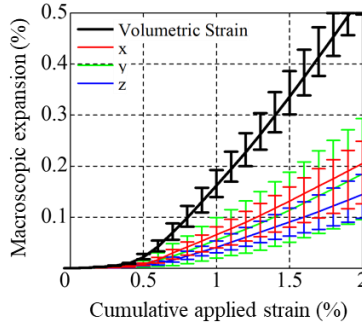
653



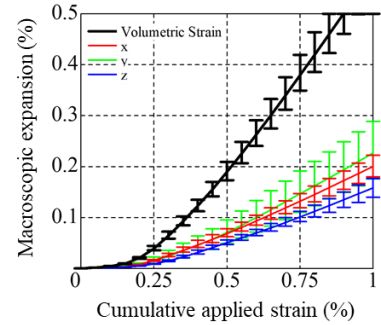
654

655

(a) 0.5%

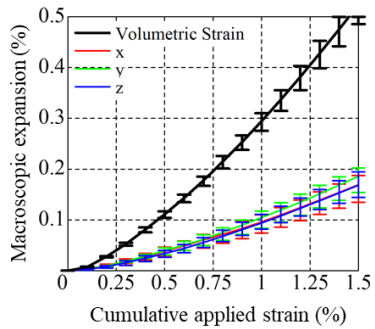


(b) 1.0%



(c) 5.0%

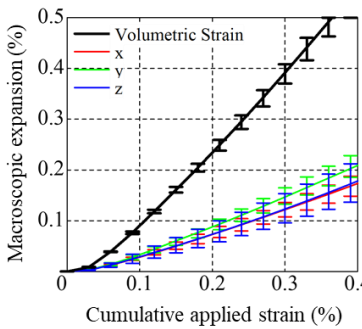
656 Figure 17 Concrete expansion evolution with cumulative applied strain of expansive sites for the gel  
657 pocket model in the case of the multi-aggregate model. The error bars are calculated from three different  
658 analytical meshes.



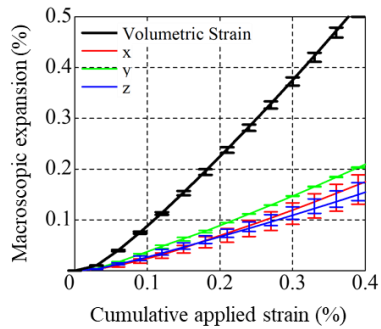
659

660

(a) Boundary model



(b) Layer model



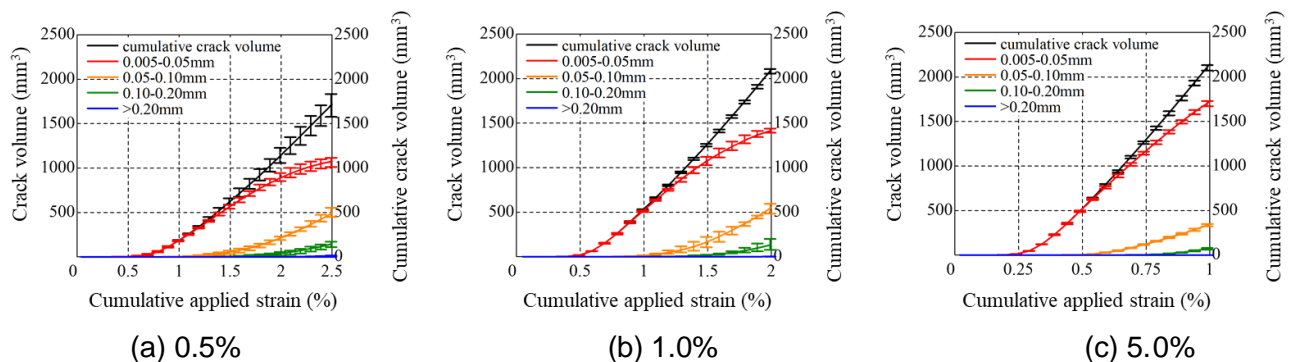
(c) Inner model

661 Figure 18 Concrete expansion evolution with the cumulative applied strain of expansive sites for the  
662 reaction rim model in the case of the multi-aggregate model. The error bars are calculated from three  
663 different analytical meshes.

664

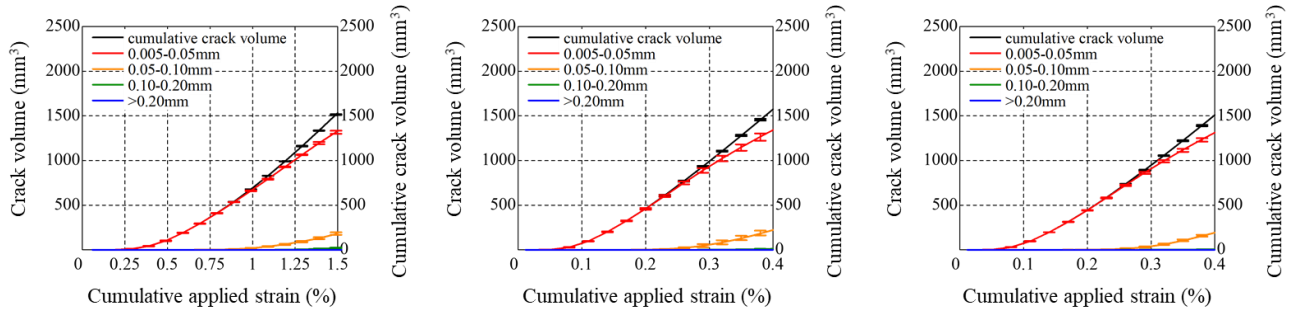
665 Further, it is possible to deduce the volume of the cracks with different opening widths  
666 for the two expansion models. Figures 19 and 20 show crack volume development with the  
667 cumulative applied strain for the gel pocket and reaction rim models, respectively. The opening  
668 of most cracks lies between 5 and 50  $\mu\text{m}$  for the two expansion models. The gel pocket model  
669 had some cracks with openings between 50 and 100  $\mu\text{m}$  and some cracks with openings

670 greater than 100  $\mu\text{m}$ ; such cracks are scarce for the numerical results obtained with the reaction  
 671 rim model. The scatter of the crack volume results for all cases is remarkably lower than the  
 672 variation in the macroscopic expansion, which suggests that the crack volume is independent  
 673 of the arrangement of aggregates even for varying crack distribution. This leads to scattered  
 674 expansion caused by the distribution of the expansive sites within the aggregate. Therefore,  
 675 the expansion is almost isotropic and slightly anisotropic for the reaction rim and gel pocket  
 676 models, respectively. In particular, the variation of expansion for the reaction rim model is less;  
 677 the variation in the crack volume is very small because of the uniformly distributed expansive  
 678 sites inside the aggregate. In the multi-aggregate model, cracks induced by the ASR can be  
 679 arrested by the presence of other aggregates, and it cannot propagate freely in one direction,  
 680 which is similar to a single aggregate model. Once crack propagation is prevented by adjacent  
 681 aggregates, new cracks can propagate in other directions, thereby leading to cracks in all  
 682 directions (Figure 15) and to expansions that are almost isotropic (Figures 17 and 18), in  
 683 contrast to results obtained with a single aggregate model. This is a key conclusion and shows  
 684 the importance of modeling the distribution of the aggregate in concrete to capture the ASR  
 685 mechanisms at the mesoscale.



686  
687

688 Figure 19 Crack volume development of the gel pocket model in the case of the multi-aggregate  
 689 model when the expansion strain reaches approximately 0.5%. The objective crack width is 0.005–  
 690 0.05, 0.05–0.10, 0.10–0.20, and larger than 0.20 mm.



691

692

(a) Boundary model

(b) Layer model

(c) Inner model

693

694

695

Figure 20 Crack volume development of the reaction rim model in the case of the multi-aggregate model when the expansion strain reaches approximately 0.5%. The objective crack width is 0.005–0.05, 0.05–0.10, 0.10–0.20, and larger than 0.20 mm.

696

## 697 5. Discussion

698

### 698 5.1 Synthesis of numerical results

699

700

701

702

703

704

705

706

707

708

709

710

711

In this analysis, the change in the expansion cracking process caused by different expansive sites inside the aggregate based on the gel pocket and reaction rim models was evaluated via mesoscale discrete modeling from a mechanical standpoint and neglecting time-dependent behavior. In the gel pocket model proposed by Dunant and Scrivener [5], the expansive site was randomly arranged inside the aggregate with different expansive site ratios (Figure 4). In the reaction rim model proposed by Ichikawa et al. [4], three expansion models were constructed assuming that expansion pressure was generated inside the reaction rim produced at the inner surface of the aggregate (Figure 5). These expansion models represented two crack expansion cases. According to the analytical results obtained with the multi-aggregate model, the cracks inside the aggregate developed and propagated between adjacent aggregates in the gel pocket model, and the cracks inside the aggregate became pronounced when the ratio increased. For the boundary model of the reaction rim model, the cracks propagated along the interface of the aggregate, and the cracks passing through the

712 aggregate were generated as the expansion progressed. Further, in the layer and inner models  
713 of the reaction rim model, many cracks appeared in the inner area of the reaction rim.  
714 Furthermore, cracks were generated between adjacent aggregates in the multi-aggregate  
715 model for both expansion models.

716

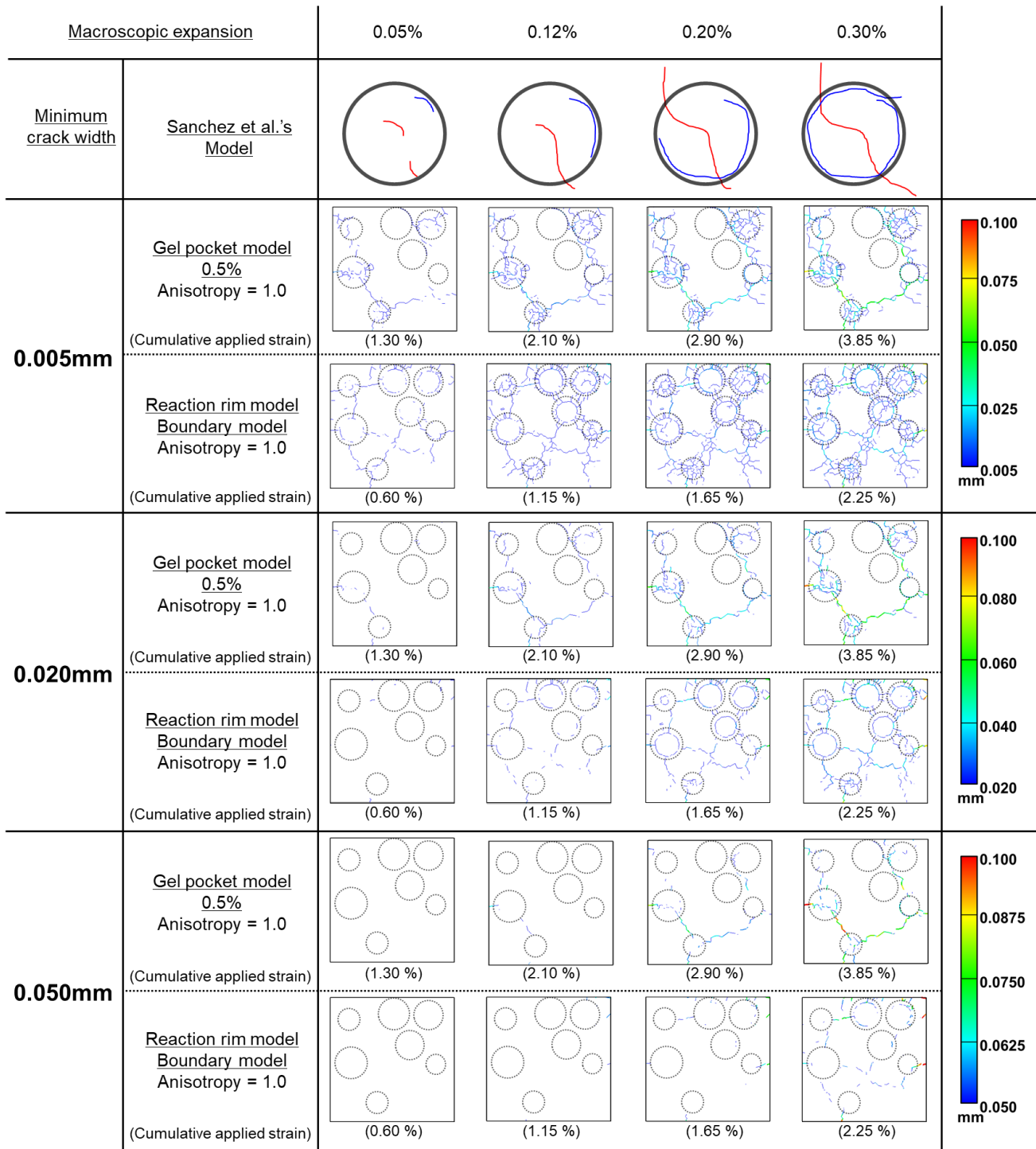
## 717 **5.2 Comparison with experimental observations**

718 The expansion cracking patterns based on the macroscopic expansion calculated by  
719 this analysis are compared with experimental observations. The analytical results of the crack  
720 propagation process were compared to Sanchez et al.'s model [11]. Sanchez et al. proposed  
721 a qualitative AAR damage model to describe the propagation process of sharp and onion skin  
722 cracks inside aggregates at several stages of macroscopic expansion (0.05, 0.12, 0.20, and  
723 0.30%). There are two problems when comparing their observations and the analytical results:  
724 the definitions of crack width and expansion.

725 The problem with defining the crack width is determining what part of cracks obtained  
726 by modeling can be observed experimentally. In general, the minimum visible crack width  
727 observable by the naked eye is considered approximately 0.05 mm. In this work, Sanchez et  
728 al. used stereomicroscopy, and therefore, the minimum crack width should be smaller than  
729 0.05 mm. For comparison, the authors investigated the change in the numerical crack  
730 development process caused by the difference in the observable minimum crack width (Figure  
731 21). The minimum crack width captured by the damage rating index (DRI) using  
732 stereomicroscopy in Sanchez et al.'s work (the magnification of the microscope was 15 times)  
733 was assumed to be between 0.003 and 0.005 mm (from a rough evaluation of 0.05 mm / 15  
734 and personal communication with Prof. Fournier). The parametric analysis was thus performed

735 with three minimum crack widths (0.005, 0.020, and 0.050 mm). The results of this analysis are  
736 shown in Figure 21, where the impact of the minimum crack width on the observations is clearly  
737 highlighted. Even though it is difficult to define the minimum crack width, the crack development  
738 process from the aggregate to the mortar phase is more precise for a smaller minimum crack  
739 width. In this study, the minimum crack width was selected to be equal to 0.02 mm, which  
740 seems to be an appropriate intermediate value. The following comparison with the  
741 experimental observation performed by Sanchez et al. is based on this assumption. The  
742 accuracy of the exact crack width is an important parameter to confirm the reasonability of the  
743 proposed model. The validation of the minimal crack width needs to be conducted in future  
744 research.

745



746

747 Figure 21 Verification of the effect of minimum crack width on the expansion crack propagation process  
 748 of the multi-aggregate model with Sanchez et al.'s model. For this model, the red and blue lines  
 749 represent "sharp cracks" and "onion skin cracks", respectively.

750

751

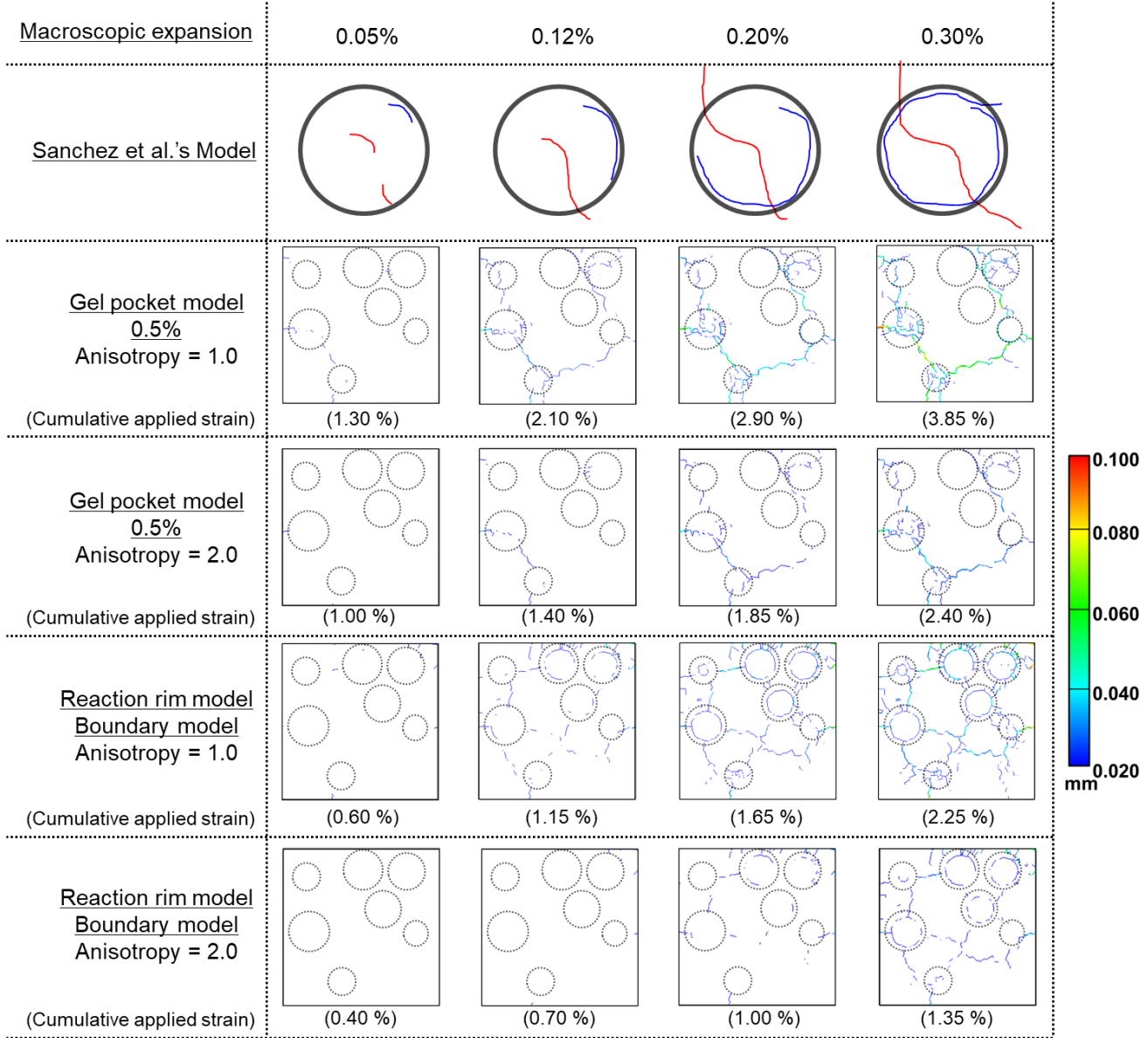
In terms of expansion, the expansion reported in [11] was measured in the longitudinal

752 direction of the cylindrical specimen. The ASR expansions measured in specimens can have  
753 anisotropy based on the casting direction. For cylindrical and prismatic specimens, the  
754 anisotropy is approximately 1.5–2.8 and 1.0–2.5 for cylindrical [38, 39] and prismatic  
755 specimens [38, 40], respectively. These varied results can be attributed to the spatial  
756 localization of the aggregates that are greatly influenced by the casting procedures; thus, the  
757 anisotropy varies with the shape of the specimens. Owing to this anisotropy, the volumetric  
758 strain of the cylindrical specimen is smaller than that of isotropic materials (three times the  
759 longitudinal expansion). Thus, the following two assumptions were considered for the definition  
760 of expansion:

- 761 - The expansion is isotropic in [11]: The volumetric expansion is equal to three times the  
762 longitudinal expansion.
- 763 - The expansion is anisotropic in the experimental work: The volumetric expansion is  
764 assumed to be equal to twice the longitudinal expansion (corresponding to an anisotropy  
765 of approximately 2 between the longitudinal and transversal expansions).

766 Figure 22 presents the corresponding crack propagation process inside the aggregate  
767 based on Sanchez et al.'s model and the analytical results of the gel pocket and reaction rim  
768 models. The expansive site ratio is 0.5% for the gel pocket model, and the expansive site for  
769 the reaction rim model is based on the boundary model. From the two assumptions above, the  
770 corresponding cumulative applied strain to the macroscopic expansion of Sanchez et al.'s  
771 model is different. Thus, the corresponding cumulative applied strain decreases as the  
772 anisotropy increases. The target expansion is calculated by the expansion of the isotropic  
773 expansion multiplied by the anisotropy, and it is consistent with the longitudinal expansion of  
774 the cylindrical specimen.





776

777 Figure 22 Validation of the expansion crack propagation process of the multi-aggregate model with  
 778 Sanchez et al.'s model (minimum crack width: 0.020 mm). For an anisotropy of 1.0, the expansion strain  
 779 of this model was calculated by the average expansion strain in the three directions. For an anisotropy  
 780 of 2.0, the expansion strain of the Sanchez et al.'s model was calculated by twice the average expansion  
 781 strain in the three directions.

782

783 In the case of the gel pocket model, the crack pattern corresponds to sharp cracking,  
 784 whereas for the boundary model, the crack pattern corresponds to onion skin cracking. In the

785 two cases, the crack process for an anisotropy of 1.0 is overestimated, while the crack process  
786 is close to Sanchez et al.'s model for an assumed anisotropy of 2.0. Thus, the crack pattern is  
787 changed because of the different expansive sites, and the crack process is consistent with  
788 experimental observations. This suggests that sharp and onion skin cracks can be explained  
789 by gel pocket and reaction rim models on the basis of mechanics. The gel pocket model can  
790 reproduce sharp cracks, and the reaction rim model can completely reproduce onion skin  
791 cracks with some rare sharp cracks.

792

### 793 **5.3 New insight on the mechanisms of microscopic ASR cracking**

#### 794 **5.3.1 Microscopic observations in the literature**

795 In actual ASR expansion, various factors related to the ASR gel production process and  
796 expansion manifestation process can impact the crack pattern. In the ASR gel production  
797 process, the production area and physical properties of ASR gel can be changed by alkali metal  
798 ion diffusion, reactions between alkali and calcium, and the distribution of the reactive silica  
799 inside the aggregates such as in veins and porous areas. With respect to the expansion  
800 manifestation process, the origin of expansion and the propagation direction of the expansion  
801 cracks can be influenced by the existence of defects inside the aggregate and their shape and  
802 distribution, reaction rim formation, bond between aggregate and cement paste/mortar,  
803 constraints applied, and aggregate shape and size distribution. Among them, the factors of  
804 influence related to the inherent characteristics of the aggregate can be the diffusion properties,  
805 distribution of the reactive silica inside aggregates, and defects inside the aggregates.

806 From these features of aggregates, the relationships between rock types and crack  
807 patterns from previous studies are summarized in Table 4. The overall target investigations

808 were 13 studies from various countries (Ben Haha et al. [6], Leemann et al. [41, 42], Chappex  
809 et al. [43], Fernandes [44], Bektas et al. [45], Ponce et al. [7], Sanchez et al. [11], Durand et al.  
810 [46], Shayan et al. [47], Katayama [48], Ichikawa et al. [4], Kawabata et al. [9]). Only data with  
811 corresponding relationships between the type of rock and crack pattern inside the aggregate  
812 that can be understood were extracted. In Table 4, the classification of rock type is indicated  
813 by small and large classifications obtained from the British Geological Survey [49–51]. The  
814 large rocks are classified into sedimentary, metamorphic, and volcanic rocks. Each rock type  
815 was further classified into three to five small classifications in this survey. Table 4 indicates that  
816 a sharp crack was confirmed for all rock types, and an onion skin crack was observed for a  
817 portion of the rocks. For example, sandstone and argillaceous rock (sedimentary rock) are  
818 composed of consolidated sand or silt/clay [49]. They potentially possess mechanically  
819 weakened areas, veins, and porous areas. In addition, schist (metamorphic rock) possesses  
820 foliated structures [50] and cracks easily along the weakened areas. These heterogeneous  
821 rocks can tend to have an easier occurrence of sharp cracks. Alternatively, relatively  
822 homogeneous rocks with less inherent defects can tend to have onion skin cracks such as  
823 andesite because the diffusion of alkali metal ions is dominant. Note that sharp cracks have  
824 been observed in rocks with fewer defects. For instance, chert is a nonclastic siliceous  
825 sedimentary rock with low porosity [49] and induces both crack patterns.

826

827

Table 4 Relationships between type of rock and crack pattern from previous investigations.

Small classification	Experimental observations											Remarks
	[6]	[41,42]	[43]	[44]	[45]	[7]	[11]	[46]	[48]	[4]	[9]	
<b>Large classification: Sedimentary rock</b>												
Limestone		S					S&O	S	S			Predominantly contains CaCO <sub>3</sub> (pp.8–10 [49])
Sandstone						S	S		S&O			Grain size: More than 32 μm (p.7 [49])
Argillaceous rock							S		S&O			Grain size: Less than 32 μm (p.7 [49])
Chert					S&O		S&O		S&O			Nonclastic siliceous sedimentary rock with less porosity (pp. 21–22 [49])
Shale									S			Contains organic carbon (p.16 [49])
<b>Large classification: Metamorphic rock</b>												
Quartzite		S		S					S			SiO <sub>2</sub> : more than 80% (p.4 [50])
Gneiss						S&O	S&O					Heterogeneous material (p.5 [50])
Schist	S		S			S			S			Strongly foliated rock (p.5 [50])
Mylonite							S&O					Foliated cohesive rock (p.8 [50])
<b>Large classification: Volcanic rock</b>												
Andesite									S&O	S&O	S&O	SiO <sub>2</sub> : more than 52% (p.13 [51])
Rhyolite							S&O		S			SiO <sub>2</sub> : 48 - 52% (p.14 [51])
Granite				S		S						Quartz + Alkali feldspar (p.35 [51])

Note that "S": sharp crack, "O": onion skin crack, "S&O": sharp and onion skin cracks as observed in SEM images.

### 831 **5.3.2 Insight from numerical mesoscale modeling**

832 The analytical results obtained in this study suggest the possibility that sharp cracks  
833 occur after the generation of onion skin cracks in the boundary model of the reaction rim model.  
834 Therefore, sharp cracks can appear because of not only a defect or localized gel pockets, but  
835 also the location of the expansive site. The crack pattern can be changed by the aggregate  
836 shape and constraint condition because of the outer cement paste/mortar. Therefore, care  
837 must be taken to ensure that the crack pattern cannot be simply classified by the rock type; it  
838 is possible that all rocks would induce both sharp cracks and onion skin cracks. The observed  
839 crack pattern depends on which cracking mechanism occurs first. The factors of influence  
840 include the texture of the aggregate, distribution of the reactive silica, existence of defects,  
841 location of the reaction rim, aggregate shape and size distribution, and surrounding condition  
842 of the aggregate. Thus, the expansion crack induced by the ASR is changed by inherent and  
843 external factors. From previous investigations, the crack pattern can be classified into sharp or  
844 onion skin cracks [11]. In this study, it was suggested that the mechanism of the formation of  
845 the two crack patterns can be explained by the spatial location of the reactive sites in the  
846 aggregate as the origins of the expansion based on the gel pocket and reaction rim models.  
847 The gel pocket model can explain the mechanism of the sharp crack formation commonly  
848 observed for heterogeneous aggregates. The reaction rim model shows onion skin cracks,  
849 which can be observed in the homogeneous aggregate and sometimes leads to rare sharp  
850 cracks. These expansion models provide the mechanisms for varying crack patterns depending  
851 on the characteristics of the aggregate.

852 - For homogeneous aggregates (highly reactive aggregates such as glassy andesite), the  
853 reaction rim model provides a correct description of the aggregate attack. The ASR leads

854 to circumferential onion skin cracking with some sharp cracks.  
855 - For heterogeneous aggregates (moderate and slowly reactive aggregates such as schist),  
856 the gel pocket model provides the most accurate representation of the reality of the location  
857 of reactive sites. Stress is then developed in the aggregate by varying the mechanical  
858 properties throughout the aggregate; the stress distribution is highly heterogeneous. This  
859 leads to a predominance of sharp cracks.

860 The different expansion models depend on the homogeneity of the aggregate, which  
861 acts on the homogeneity of the penetration of alkalis and the reactive silica distribution. Thus,  
862 the dominant expansion model can be changed based on aggregate homogeneity. If aggregate  
863 homogeneity is mild, expansion and cracking are based on the combination of both expansion  
864 models; further, a combination of cracking patterns may be present.

865

## 866 **6. Conclusions**

867 This study aimed to investigate the influence of the origins of expansion on the ASR  
868 crack propagation process through numerical analysis. The authors developed a mesoscale  
869 discrete model and applied it to represent concrete with aggregate particles and a mortar phase  
870 based on 3D-RBSM. With this mesoscale discrete model, the expansive sites were arranged  
871 inside the aggregate based on two ASR-expansion mechanisms from the literature (gel pocket  
872 model and reaction rim model). The ASR expansions and cracking patterns were investigated  
873 by applying strain to the expansive sites. The expansion crack propagation processes  
874 calculated by the gel pocket and reaction rim models were compared with previous experiments  
875 drawn from the literature. The findings are listed as follows:

876

- 877 1) Regardless of the expansion model applied in the mesoscale approach, the multi-  
878 aggregate model was found to be necessary to obtain realistic three-dimensional  
879 expansion and cracking. The single aggregate model leads to highly unstable and unique  
880 cracks propagating from the mortar to the aggregate. A realistic aggregate distribution  
881 needs to be modeled to reproduce a realistic distribution of expansion cracks for  
882 analyzing the ASR mechanisms.
- 883 2) The crack propagation process obtained with the gel pocket model has two stages: first,  
884 the cracks are generated around the expansive sites inside the aggregate, and then, they  
885 subsequently pass through the aggregate and propagate between adjacent aggregates  
886 with increasing expansion.
- 887 3) The crack propagation of the reaction rim model has two stages: first, the cracks are  
888 generated inside along the boundary of the aggregate for the boundary and layer models.  
889 Subsequently, the cracks propagate from the aggregate to the mortar with increasing  
890 expansion, and many cracks are observed at the entire aggregate area for the inner  
891 model. As the expansive sites exist locally at the external boundary of the aggregate,  
892 cracks along the boundary of the aggregate can be easily observed.
- 893 4) The crack propagation process inside the aggregate (sharp crack/onion skin crack)  
894 simulated with the gel pocket model and boundary model of the reaction rim model is  
895 consistent with the previous experimental classification proposed by Sanchez et al. [11].
- 896 5) From the summary of the relationships between rock type and crack pattern obtained  
897 from the literature, it was found that the expansion crack induced by ASR is inherently  
898 changed. For an equal level of macroscopic expansion, cracking in the aggregate and in  
899 concrete is not equal based on the distribution of reactive sites in the aggregate. This can

900 lead to different macroscopic damages for an equal level of expansion.

901 6) The two expansion models highlight the different crack patterns obtained according to  
902 the nature of the aggregate. For homogeneous aggregates (highly reactive aggregates  
903 such as glassy andesite), the reaction rim model provides a correct description of the  
904 aggregate attack. In such conditions, ASR leads to circumferential onion skin cracking  
905 and some sharp cracks. For heterogeneous aggregates (moderate and slowly reactive  
906 aggregates such as schist), the gel pocket model provides the most accurate  
907 representation of the actual location of reactive sites. Stress is then developed in the  
908 aggregate with mechanical properties varying throughout the aggregate, and the stress  
909 distribution is highly heterogeneous. This leads to a predominance of sharp cracks.

910

## 911 **Acknowledgements**

912 The authors would like to thank Prof. B. Fournier (Laval University) for insightful discussions  
913 about the width of cracks observed with stereomicroscope.

914

## 915 **References**

916 [1] Taylor H. F. W., 1997, Cement chemistry 2nd edition, Thomas Telford.

917 [2] Rajabipour F., Giannini E., Dunant C., Ideker J. H., Thomas M. D. A, 2015, Alkali-silica  
918 reaction: Current understanding of the reaction mechanisms and the knowledge gaps,  
919 Cement and Concrete Research, Vol. 76, pp. 130-146.

920 [3] Shi Z., Geng G., Leemann A., Lothenbach B., 2019, Synthesis, characterization, and water  
921 uptake property of alkali-silica reaction products, Cement and Concrete Research, Vol. 121,  
922 pp. 58-71.



- 923 [4] Ichikawa T., Miura M., 2007, Modified model of alkali-silica reaction, Cement and Concrete  
924 Research, Vol. 37, pp. 1291-1297.
- 925 [5] Dunant C., Scrivener K. L., 2010, Micro-mechanical modeling of alkali-silica-reaction-  
926 induced degradation using the AMIE framework, Cement and Concrete Research, Vol. 40,  
927 pp. 517-525.
- 928 [6] Ben Haha M., Gallucci E., Guidoum A., Scrivener K., 2007, Relation of expansion due to  
929 alkali silica reaction to the degree of reaction measured by SEM image analysis, Cement  
930 and Concrete Research, Vol. 37, pp. 1206-1214.
- 931 [7] Ponce J. M., Batic O. R., 2006, Different manifestations of the alkali-silica reaction in  
932 concrete according to the reaction kinetics of the reactive aggregate, Cement and Concrete  
933 Research, Vol. 36, pp. 1148-1156.
- 934 [8] Yamamoto Y., Nakamura H., Kuroda I., Furuya N., 2014, Crack propagation analysis of  
935 reinforced concrete wall under cyclic loading using RBSM, European Journal of  
936 Environmental and Civil Engineering, Vol. 18, No. 7, pp. 780-792.
- 937 [9] Kawabata Y., Dunant C., Yamada K., Scrivener K., 2019, Impact of temperature on  
938 expansive behavior of concrete with a highly reactive andesite due to the alkali-silica  
939 reaction, Cement and Concrete Research, Vol. 125, 105888.
- 940 [10] Shi Z., Park S., Lothenbach B., Leemann A., 2020: Formation of shlykovite and ASR-P1 in  
941 concrete under accelerated alkali-silica reaction at 60 and 80 °C, Cement and Concrete  
942 Research, Vol. 137, 106213.

- 943 [11]Sanchez L. F. M., Fournier B., Jolin M., Duchesne J., 2015, Reliable quantification of AAR  
944 damage through assessment of the Damage Rating Index (DRI), *Cement and Concrete*  
945 *Research*, Vol. 67, pp. 74-92.
- 946 [12]Reinhardt H. W., Mielich O., 2011, A fracture mechanics approach to the crack formation  
947 in alkali-sensitive grains, *Cement and Concrete Research*, Vol. 41, pp. 255-262.
- 948 [13]Furusawa Y., Ohga H., Uomoto T., 1994, An analytical study concerning prediction of  
949 concrete expansion due to alkali-silica reaction, in: Malhotra (Ed.), 3rd International  
950 Conference on Durability of Concrete, Nice, France, SP 145-40, pp. 757-780.
- 951 [14]Poyet S., Sellier A., Capra B., Foray G., Torrenti J.-M., Cognon H., Bourdarot E., 2007,  
952 Chemical modeling of alkali silica reaction: influence of the reactive aggregate size  
953 distribution, *Material and Structures*, Vol.40, pp.229-239.
- 954 [15]Comi C., Fedele R., Perego U., 2009, A chemo-thermo-damage model for the analysis of  
955 concrete dams affected by alkali-silica reaction, *Mechanics of Materials*, Vol. 41, pp. 210-  
956 230.
- 957 [16]Charpin L., Ehrlacher A., 2014, Microporomechanics study of anisotropy of ASR under  
958 loading, *Cement and Concrete Research*, Vol. 63, pp. 143-157.
- 959 [17]Takahashi Y., Ogawa S., Tanaka Y., Maekawa K., 2016, Scale-dependent ASR expansion  
960 of concrete and its prediction coupled with silica gel generation and migration, *Journal of*  
961 *Advanced Concrete Technology*, Vol. 14, pp. 444-463.

- 962 [18]Saouma V. E., Martin R. A., Hariri-Ardebili M. A., Katayama T., 2015, A mathematical  
963 model for the kinetics of the alkali-silica chemical reaction, Cement and Concrete Research,  
964 Vol. 68, pp. 184-195.
- 965 [19]Multon S., Sellier A., Cyr M., 2009, Chemo-mechanical modeling for prediction of alkali  
966 silica reaction (ASR) expansion, Cement and Concrete Research, Vol. 39, pp. 490-500.
- 967 [20]Grimal E., Sellier A., Le Pape Y., Bourdarot E., 2008, Creep, shrinkage, and anisotropic  
968 damage in alkali-aggregate reaction swelling mechanism-Part I. A constitutive model, ACI  
969 Mater. J. Vol. 105, pp.227–235.
- 970 [21]Multon S., Sellier A., 2016, Multi-scale analysis of alkali-silica reaction (ASR): Impact of  
971 alkali leaching on scale effects affecting expansion tests, Cement and Concrete Research,  
972 Vol. 81, pp. 122-133.
- 973 [22]Dunant C. F., Scrivener K. L., 2012, Effects of aggregate size on alkali-silica-reaction  
974 induced expansion, Cement and Concrete Research, Vol. 42, pp. 745-751.
- 975 [23]Dunant C. F., Scrivener K. L., 2012, Effects of uniaxial stress on alkali-silica reaction  
976 induced expansion of concrete, Cement and Concrete Research, Vol. 42, pp. 567–576.
- 977 [24]Giorla A. B., Scrivener K., Dunant C., 2015, Influence of visco-elasticity on the stress  
978 development induced by alkali-silica reaction, Cement and Concrete Research, Vol. 70, pp.  
979 1-8.
- 980 [25]Alnaggar M., Cusatis G., Luzio G. D., 2013, Lattice Discrete Particle Modeling (LDPM) of  
981 Alkali Silica Reaction (ASR) deterioration of concrete structures, Cement and Concrete  
982 Composites, Vol. 41, pp. 45-59.

- 983 [26]Wang Y., Meng Y., Jiradilok P., Matsumoto K., Nagai K., Asamamoto S., 2019, Expansive  
984 cracking and compressive failure simulations of ASR and DEF damaged concrete using a  
985 mesoscale discrete model, *Cement and Concrete Composites*, Vol. 104,  
986 (<https://doi.org/10.1016/j.cemconcomp.2019.103404>).
- 987 [27]Iskhakov T., Timothy J. J., Meschke G., 2019, Expansion and deterioration of concrete due  
988 to ASR: Micromechanical modeling and analysis, *Cement and Concrete Research*, Vol.  
989 115, pp. 507-518.
- 990 [28]Kawai T., 1978, New discrete models and their application to seismic response analysis of  
991 structure, *Nuclear Engineering and Design*, Vol. 48, pp. 207-229.
- 992 [29]Nakamura H., Iwamoto T., Fu L., Yamamoto Y., Miura T., Hanifi Y. G., 2018, Shear  
993 resistance mechanism evaluation of RC beams based on arch and beam actions, *Journal*  
994 *of Advanced Concrete Technology*, Vol. 16, pp. 563-576.
- 995 [30]Zhara A., Qiao D., Nakamura H., Miura T., Yamamoto Y., 2018, Development of simulation  
996 method of concrete cracking behavior and corrosion products movement due to rebar  
997 corrosion, *Construction and Building Materials*, Vol. 190, pp. 560-572.
- 998 [31]Yang Y., Nakamura H., Yamamoto Y., Miura T., 2020, Numerical simulation of bond  
999 degradation subjected to corrosion-induced crack by simplified rebar and interface model  
1000 using RBSM, *Construction and Building Materials*, Vol. 247,  
1001 (<https://doi.org/10.1016/j.conbuildmat.2020.118602>).
- 1002 [32]Nakamura H., Srisoros W., Yashiro R. Kunieda M., 2006, Time-dependent structural  
1003 analysis considering mass transfer to evaluate deterioration process of RC structures,  
1004 *Journal of Advanced Concrete Technology*, Vol. 4, pp. 147-158.

- 1005 [33]Miura T., Maruyama I., Nakamura H., Yamamoto Y., 2017, Feedback space of ion transfer  
1006 through cracks during deterioration mortar due to sulfate attack evaluated by RBSM-Truss  
1007 Network Model, Journal of Advanced Concrete Technology, Vol. 15, pp. 610-626.
- 1008 [34]Thomure J., Bolander J. Jr., Kunieda M., 2001, Reducing mesh bias on fracture within  
1009 Rigid-Body-Spring Networks, Structural Eng./Earthquake Eng., JSCE, Vol. 18, No. 2, pp.  
1010 95-103.
- 1011 [35]JSCE, 2017, Standard Specifications for Concrete Structures -Design-.
- 1012 [36]Sellier A., 2018, Anisotropic Damage and Visco-Elasto-Plasticity Applied to Multiphase  
1013 Materials. LMDC - Laboratoire Matériaux et Durabilité des Constructions de Toulouse;  
1014 Université de Toulouse III - Paul Sabatier; INSA de Toulouse.
- 1015 [37]Morenon P., Multon S., Sellier A., Grimal E., Hamon F., Bourdarot E., 2017, Impact of  
1016 stresses and restraints on ASR expansion, Construction and Building Materials, Vol. 140,  
1017 pp. 58-74.
- 1018 [38]Smaoui N., Berube M.-A., Fournier B., Bissonnette B., 2004, Influence of specimen  
1019 geometry, orientation of casting plane, and mode of concrete consolidation on expansion  
1020 due to ASR, Cement, Concrete, and Aggregates, Vol. 26, No. 2, pp. 1-13.
- 1021 [39]Multon S., Seignol J.-F., Toutlemonde F., 2005, Structural behavior of concrete beams  
1022 affected by alkali-silica reaction, ACI materials journal, Vol. 102, No. 2, pp. 67-76.
- 1023 [40]Tarek U. M., Hamada H., Yamaji T., 2003, Relation between strain on surface and strain  
1024 over embedded steel bars in ASR affected concrete members, Journal of Advanced  
1025 Concrete Technology, Vol. 1, No. 1, pp. 76-88.

- 1026 [41]Leemann A., Merz., 2013, An attempt to validate the ultra-accelerated microbar and the  
1027 concrete performance test with the degree of AAR-induced damage observed in concrete  
1028 structures, *Cement and Concrete Research*, Vol. 49, pp. 29-37.
- 1029 [42]Leemann A., 2017, Raman microscopy of alkali-silica reaction (ASR) products formed in  
1030 concrete, *Cement and Concrete Research*, Vol. 102, pp. 41-47.
- 1031 [43]Chappex T., Sofia L., Dunant C., Scrivener K., 2016, A robust testing protocol for the  
1032 assessment of ASR reactivity of concrete, *Proceedings of 15th International Conference*  
1033 *on Alkali-Aggregate Reaction in Concrete*, 15ICAAR2016\_225.
- 1034 [44]Fernandes I., 2009, Composition of alkali-silica reaction products at different location within  
1035 concrete structure, *Materials Characterization*, Vol. 60, pp. 655-668.
- 1036 [45]Bektas F., Turanli L., Topal T., Goncuoglu M. C., 2004, Alkali reactivity of mortars  
1037 containing chert and incorporating moderate-calcium fly ash, *Cement and Concrete*  
1038 *Research*, Vol. 34, pp. 2009-2214.
- 1039 [46]Durand B., Fournier B., 2016, 20-year results of an in-situ monitoring study of large  
1040 concrete electrical tower foundations affected by alkali-silica reaction (ASR), *Proceedings*  
1041 *of 15th International Conference on Alkali-Aggregate Reaction in Concrete*,  
1042 15ICAAR2016\_195.
- 1043 [47]Shayan A., Al-Mahaidi R., Xu A., 2008, Durability and strength assessment of AAR-affected  
1044 bridge deck planks, *Proceedings of 13th International Conference on Alkali-Aggregate*  
1045 *Reaction in Concrete*, pp. 422-433.

- 1046 [48]Katayama T., 1997, Petrography of alkali-aggregate reactions in concrete—reactive  
1047 minerals and reaction products, Proceedings of East Asia Alkali-Aggregate Reaction  
1048 Seminar, pp. A45-A59.
- 1049 [49]Hallsworth C. R., Knox R. W. O'B, 1999, BGS Rock Classification Scheme, Volume 3,  
1050 Classification of sediments and sedimentary rocks, British Geological Survey Research  
1051 Report (2nd Edition), RR99-03.
- 1052 [50]Robertson S., 1999, BGS Rock Classification Scheme, Volume 2, Classification of  
1053 metamorphic rocks, British Geological Survey Research Report (2nd Edition), RR99-02.
- 1054 [51]Gillespie M. R., Styles M. T., 1999, BGS Rock Classification Scheme, Volume 1,  
1055 Classification of igneous rocks, British Geological Survey Research Report (2nd Edition),  
1056 RR99-06.