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1	Modelling of autogenous healing in Ultra High Performance Concrete
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3	
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9	Highlights
10	- A hydro-chemo-mechanical model of autogenous healing of concrete is developed.
11	- Mechanical properties of the healed crack are assessed.
12	- Quantification of the healing product mechanical properties is proposed.
13	
14	Abstract
15	The restoration of ultra high performance concrete (UHPC) specimens due to the self-
16	healing phenomenon was investigated in this paper. A hydro-chemo-mechanical model
17	based on micro-mechanical observations was established. The aim was to evaluate the
18	mechanical properties of the new healing products in order to describe the partial recovery
19	of the mechanical properties of healed concrete. An analysis of the influence of some
20	physical parameters provided first explanations about the self-healing phenomenon. It
21	was shown that the mechanical properties of CSH in the healed crack are lower than the
22	ones of the virgin material.
23	

24 Keywords: Self-healing (C), Modelling (E), Mechanical properties (C), Calcium-

25 Silicate-Hydrate (C-S-H) (B), Characterization (B)

#### 26 1. Introduction

27 Although occurrence of cracks in concrete structures is taken into consideration during design, cracks generate important inspection and repairing costs. Some of them can 28 29 seriously affect the durability and the stability of the structures. Thus, self-healing 30 concrete could be a mean to make important savings decreasing direct and indirect costs 31 caused by repairing works [1, 2]. It has been observed by many researchers that cracks in 32 concrete can heal naturally, without any particular additive, under favourable conditions 33 [3-11]. This phenomenon called 'autogenous' healing is the consequence of two main 34 reactions [12]: further hydration of unhydrated particles upon water ingress into the crack, especially for concrete with an important amount of unhydrated cement particles [13, 14] 35 and precipitation of calcium carbonate due to the reaction between calcium contained in 36 the cementitious matrix with carbon dioxide dissolved in the water filling the crack [15]. 37 38 Some studies have reported the predominance of the precipitation phenomenon in common concrete with a water-to-cement (w/c) ratio around 0.5 leading to the filling of 39 40 cracks with an initial width up to around 200 µm [10]. Autogenous healing by further 41 hydration has been studied by several researchers because of expected mechanical regains 42 due to the creation of new calcium silicate hydrates (C-S-H). A global recovery of 43 stiffness can be achieved by further hydration [16, 18]. But, regains in compressive or 44 flexural strengths have been found to be limited [8, 10, 14] because of relatively poor 45 mechanical properties of the healing product.

Only few models were developed to describe self-healing of concrete. Some models were proposed to determine the amount of unhydrated cement particles in concrete specimens considering w/c ratio and cement fineness which underlies the self-healing potential [17, 19, 20], or to calculate the amount of healing product due to further hydration considering two crack modes [21, 22]. Recently, Huang and Ye [23, 24] developed a model simulating

further hydration by water release by a capsule in a crack using water transport theory, ion diffusion theory and thermodynamics theory. However, these models do not provide any information about the mechanical effects of self-healing.

54 In this study, a hydro-chemo-mechanical model was developed to simulate autogenous 55 healing by further hydration with the aim to explain the mechanical regains after healing 56 and provide information about the self-healing product. Experimentally, Granger et al. 57 [14] used ultra high performance cementitious material (UHPC) with a w/c ratio close to 58 0.2 to study the self-healing of small cracks with initials widths of 10, 20 and 30  $\mu$ m. Mechanical properties of healed and uncracked specimens were compared at different 59 stages (1 week, 3 weeks, 10 weeks, 20 weeks and 40 weeks). The hydro-chemo-60 mechanical model has been implemented in the finite element code Cast3M [25] to 61 calculate the self-healing potential of a damaged concrete beam after cracking using 62 three-point-bending test. Damage has been calculated by a modified microplane model 63 [26, 27]. Ingress of water has been simulated by the Fick's law and water interaction with 64 65 the unhydrated cement particles led to their hydration considering a hydration model [28, 66 29]. The recovery of mechanical properties of the cracked concrete beam was obtained 67 by decreasing the local damage value due to the filling of empty spaces by new hydrates. 68 In the first part of this article, the relationships underlying the model will be explained 69 into details and the model algorithm will be presented. Furthermore, the numerical results 70 will be compared with experimental measurements and an analysis of the self-healing 71 phenomenon will be suggested.

72

73

### 74 **2.** Description of the self-healing model

75 **2.1. Problem formulation** 

The resolution of the global problem consists on the resolution of a first mechanical problem (P1) corresponding to the initial creation of a single crack, followed by a coupled hydro-chemical problem corresponding to the healing process (P2), and is concluded by a second resolution of a mechanical problem (P3) due to the mechanical changes implicated by the healing process.

We consider a volume V representing the specimen. The specimen is submitted to successive loads of different types: displacements  $\overline{U}_i$  are applied on the boundaries  $\Gamma_i^u$ , the force  $\overline{F}$  is applied on the boundary  $\Gamma^{\sigma}$ , the velocity (or pressure, or concentration) is applied on the boundary  $\Gamma^c$ . The problems P1 and P3 are similar and lead to the calculation of the local displacement fields  $(\overline{u}(\overline{y}))$ , strain fields  $(\overline{\varepsilon}(\overline{y}))$  and stress fields  $(\overline{\sigma}(\overline{y}))$  as follow (where volume forces are negligible):

87 
$$\overline{div\sigma} = \overline{0}$$
  $\overline{y} \in V$  (1)

88 
$$\overline{\sigma}(\overline{y}) = (1 - d(\overline{y}))\widetilde{C}^{t}(\overline{y}) : (\overline{\varepsilon}(\overline{y}) - \overline{\varepsilon}^{-p}(\overline{y}))$$
  $\overline{y} \in V$  (2)

89 
$$\overline{\varepsilon}(\overline{y}) = \frac{1}{2} \left( \overline{\nabla} \overline{u}(\overline{y}) + \sqrt{\nabla} \overline{u}(\overline{y}) \right) \qquad \overline{y} \in V$$
 (3)

90 
$$\overline{u}(\overline{y}) = \overline{U}_i$$
  $\overline{y} \in \Gamma_i^u$  (4)

91  $\overline{F} = \overline{\sigma}(\overline{y}).\overline{n}$   $\overline{y} \in \Gamma^{\sigma}$  (5)

92 where  $\widetilde{C}^{t}(\overline{y})$  represents the local stiffness tensor of 4<sup>th</sup> order depending on the time (t = 93 0 corresponds to the problem P1, and t > 0 corresponds to the problem P3) and  $\overline{\varepsilon}^{p}$  the 94 plastic strain (computed using a loading function by the normality rule). The evolution of95 the damage is given by [27]:

96 
$$d = 1 - \frac{\varepsilon_{d0}}{\varepsilon_{eq}} \exp[B_t(\varepsilon_{d0} - \varepsilon_{eq})]$$
(6)

97 where  $B_t = \frac{f_t}{\frac{G_f}{h} - \frac{f_t \cdot \mathcal{E}_{d_0}}{2}}$  represents a damage parameter to control the slope of the

98 strain softening constitutive relation in function of the width h of the finite element and

99 the fracture energy [36],  $\varepsilon_{d0} = \frac{f_i}{E}$  the strain threshold and  $\varepsilon_{eq}$  the equivalent strain

100  $(\varepsilon_{eq} = \sqrt{\varepsilon}^{ee} = \varepsilon)$  where  $\varepsilon^{e}$  is the elastic strain).

101 To model the autogenous self-healing (problem P2), external humidity conditions are 102 considered by the contact with water on the boundary of the beam (initial concentration 103 of water of 1 outside the beam, 0.2 inside the beam). The ingress of water, with a speed 104 U, through the damaged material was simulated by using the Fick's law:

105 
$$\frac{\partial U}{\partial T} = D(d) \frac{\partial^2 U}{\partial X^2}$$
 (7)

where D(d) represents the diffusion coefficient depending on damage [30, 31]. The evolution of the diffusivity coefficient is calibrated to follow the evolution of the permeability coefficient with damage (eq 8) [31, 32]. For small damage values, it corresponds to an exponential law and for damage values close to 1, it fits the Poiseuille's law. The evolution of the diffusivity coefficient D(d) is presented in Figure 1.

111 
$$\log(k) = (1-d)\log(k_p) + d\log(k_d)$$
 (8)

112 Where  $k_p = u^2/12$  is the permeability for damage close to 1 (u is the crack opening) and

113  $k_d = k_0 \exp((\alpha D)^{\beta})$  is the permeability for small damage values between 0 and 0.15 (k0

114 is the initial permeability,  $\alpha$  and  $\beta$  two constants ranging respectively from 9.4 to 12.3 115 and 1.4 to 1.6) [30].

116

117 The local quantity of water inside the beam is then used to activate the hydration process 118 which determines the volume of each component in the microstructure according to 119 Arrhenius' equation [28, 29]:

120 
$$\tau_i \frac{d\xi_i}{dt} = \tilde{z}_{\tau_i \tau_i}$$

121 where  $\tilde{A}$  and  $\tau$  represent the normalized affinity and the characteristic time, respectively, 122  $\xi_i$  the hydration coefficient of the clinker i.

123 The hydration process leads to the dissolution of clinkers and to the formation of hydrates124 with a volume defined by:

125 
$$V_{k}^{P}(t) = \sum_{l}^{n} \left( V_{l}^{0} \frac{n_{k}^{P} M_{k}}{n_{l}^{R} M_{l}} \frac{\rho_{C}}{\rho_{k}} \right) \xi_{l}(t) \qquad k = 1, m$$
(10)

126 where  $V_i^0$  represents the residual clinkers in concrete,  $V_k^p$  the new formed hydrates, M the 127 molar mass,  $\rho$  the mass density and n the mole. The index k represents the products 128 (clinkers), l the reactants and c the cement.

According to the definition of damage as a void volume in the material, we suppose that when the hydration products are created in the damage area, they fill the empty space and decrease the local damage value:

132 
$$d_{final} = d_{initial} - k \frac{V_{hydrates}}{V_{total}}$$
(11)

133

Where k is a coefficient to eventually adjust the final damage value after healing due to the healing potential, a value of 1 is considered in this study. Up to now, the contribution of a given healing product from autogenous healing to the observed regain in mechanical properties is not evident. In the experimental results reported here, almost no calcite was formed, so the coefficient k should be higher than for other concrete were the healing product is a mix of CSH, portlandite and calcite. One should adjust the coefficient k to the effective amount of CSH product created by further hydration.

141 The decrease of the local damage value leads to a decrease of the quantity of water 142 absorbed into the crack during the following time step due to the decrease of the diffusion

143 coefficient.

144 A condensed flowchart of the model is presented in Figure 2.

145

## 146 **2.2. Modelling system**

Finite element analysis were performed on a UHPC notched beam (50 cm x 10 cm x 5 cm) with a notch depth of 2 cm as used by Granger et al. [14]. The centre part of the beam was discretized with elements of 0.75 mm x 1 mm size. Three-point-bending tests were simulated on a concrete beam before and after healing to simulate, respectively, the creation of a single crack, and the restoration of the mechanical properties.

The numerical simulations have been performed under displacement control with constant displacement step of  $5 \times 10^{-7}$  m at the top of the beam, considering a vertical displacement of the notch where the load was applied and rolling supports under the beam as illustrated in Figure 3. The crack mouth opening displacement (CMOD) was calculated considering the evolution of the relative displacement of two nodes placed under the beam, at the same position as in the experimental instrument (1 cm of initial opening).

158 For the healing procedure, an initial moisture diffusion coefficient of  $10^{-9}$  m<sup>2</sup>/s was

159 considered for undamaged zones [33].

In order to describe the hydration process at a mesoscopic scale, an initial uniform volume fraction of clinker of 0.12 was applied. This initial volume fraction corresponds to a volume fraction of anhydrous clinkers of around 50% in the cement paste. The local volume fraction of clinker was decreased at each time step after the diffusion of water according the pre-set hydration speed. The first hydration speed considered in this study was comparable to a speed of a new concrete mix. The hydration speed was then decreased to investigate its role on the healing kinetics.

167 Different numerical time steps were investigated from 1 second to 6 hours after several

168 days of healing.

169

### 170 **3. Results and discussion**

## 171 **3.1.** Pre-cracking stage and mechanical parameters of the virgin specimen

172 Some constitutive damage parameters (Young's modulus (E), Poisson's ratio (v), tensile and compressive strengths ( $f_t$  and  $f_c$ )) were measured experimentally and fracture energy 173 174 (G<sub>f</sub>) was adjusted to perform the three-point-bending simulations on a notched beam, in order to fit the experimental loading curves during the stage of the creation of the crack. 175 176 The selected parameters for the mechanical model are presented in Table 1. These 177 parameters gave correct initial stiffness and maximal bearing load and also led to a correct 178 agreement concerning the unloading slope and the final CMOD (around 10 µm) as 179 illustrated in Figure 4. The latter are important in scope to fairly compare numerical and 180 experimental reloading results.

181

182 **3.2. Healing** 

183 **3.2.1.** Influence of the healing parameters on the extend of the healed zone

184 Healing is located all along the crack if the evolution of the diffusion coefficient with 185 damage is the one previously presented. Indeed, diffusion through the crack only takes 186 tens of seconds while the hydration process duration is of around some hours. If the speed 187 of hydration is increased (which seems to be a relevant hypothesis because the high water 188 content in the crack [24] and the direct exposure of clinker on the crack surface), damage 189 can decreased faster locally. Then, the healed zone is located at the bottom part of the 190 crack (Figure 5) because the local reduction of the damage slows down the diffusion 191 process. Thus, the healed zone grows slowly to the top of the beam.

192 Experimentally, healing products (mainly C-S-H) are generally observed all along the crack [14, 34]. The model can reproduce this trend even though it existed risk of the 193 partial filling of the crack due to its small width. However, this first model considering 194 195 the water diffusion and the hydration of anhydrous clinker is rather sensitive to the input parameters (speed of rehydration and speed of diffusion as illustrated in Figure 5). Due 196 to the dependence of the model on the speed of rehydration, the choice has been made to 197 198 develop an external procedure to localise the healing product to focus on the mechanical 199 part of the model in order to identify material parameters of the healing product.

200

## 3.2.2. External localisation procedure and two-phase healing model

201 In order to limit the dependence of the results on the speed on hydration of clinkers, an 202 external procedure (independent of the hydro-chemical procedure) was developed to 203 localise the healed zone considering the initial crack width and study its influence without 204 taking into consideration the diffusion process described earlier. This procedure was 205 developed to easily study the influence of the size of healed zone on the mechanical 206 regains. Considering that it was not possible to input variably distributed mechanical 207 properties in this external procedure (to represent the evolution of the filling fraction for 208 example), mechanical parameters corresponding to the healing product were input in the

bottom part of the beam, where the water can react directly with the clinker and fill the crack very quickly. For larger cracks, it is possible that the majority of the healing products could be located where the local crack width would be reasonable (< 100 - 200 microns [10]).

Numerical calculation of the initial crack width was performed according to OUVFISS
procedure implemented in Cast3M [35]. Figure 6 a) represents the initial numerical crack
width. The initial crack width calculated with this procedure is 8.6 µm. It consists well
with the measured CMOD around 10.

A two-phase healing model, illustrated in Figure 6 b), was then developed to study the 217 influence of the mechanical parameters of the healing product on the global mechanical 218 behaviour. The bottom part of the crack, corresponding to the zone where the crack width 219 220 was larger than the width input in the localisation procedure, was modelled with mechanical parameters independent of the parameters of the virgin specimen. This zone 221 222 (Z1) situated in the bottom part of the crack is supposed to model the C-S-H healing 223 product. Other mechanical parameters were attributed to the upper part of the crack. This 224 zone (Z2) is supposed to model the mechanical properties of all the others entities present in the crack except the C-S-H healing product. Although the model does not take into 225 226 account the experimental localisation of the healing product all along the crack, it allows 227 representing the gradient of properties existing in the crack.

228

## **3.3. Reloading**

230

### **3.3.1.** Influence of the extend of the healed zone

Because the main interest of the hydro-chemical procedure is the localisation of the healed zone, the influence of this localisation on the mechanical properties of the healed specimen was firstly studied. Several reloading with different healed zone sizes and localisations were simulated assuming the same mechanical properties for the healingproduct than for the virgin specimen (damage locally reduced to 0).

236 When the bottom part of the crack was not healed, the initial slope of the reloading curve 237 in the load vs CMOD graph was smaller than all the experimental results with healing. 238 This could indicate that healing products were formed at the bottom part of the crack even 239 if it was the wider part of the crack. It could be explained by the small maximum aperture 240 of the crack which is comparable to the size of the unhydrated clinker and therefore more 241 likely to be closed by hydration products. The healing localisation may be different for wider cracks with maximum crack width of around 100-300 µm because hydration 242 products (C-S-H) cannot fill this gap completely as reported by many experimental 243 244 studies [10, 15, 17].

On the other hand, healing in the bottom part of the crack is not sufficient to restore the 245 mechanical properties (stiffness and maximum bearing load) even if the healing product 246 has the same mechanical properties as the virgin specimen. Extend of the healed zone 247 248 needs to be sufficient. In our model, a height of the healed zone of around one fourth of 249 the crack length (zone where the initial crack width is larger than 7  $\mu$ m) seems sufficient 250 to restore the initial slope of the load vs. CMOD curve and also the maximum bearing 251 load as illustrated in Figure 7. If the healed zone is too small (zone where the initial crack width is larger than 8-8.5 µm which leads to a length of the healed zone of around one 252 253 eighth to one tenth of the initial crack length) the maximum bearing load and the stiffness 254 cannot consist well with experimental results. In this case, the maximum bearing load 255 increases with the size of the healed zone.

Thus, according to the experimental results showing a rather quick regain in stiffness(different than the hysteresis phenomenon) and the numerical calculations, we can assume

that healing product was, at least, created at the bottom part of the crack and likely recoveran extended part of the crack.

- 260
- 261

### **3.3.2.** Influence of the mechanical parameters of the healing product

As exemplified by Figure 7, the experimental bi-linear shape of the reloading curve cannot be reproduced assuming that the healing product has the same mechanical properties than the virgin specimen. Consequently, new mechanical parameters were input to describe the healing product with the two-phase healing model. Thus, it is possible to simulate a healing product with heterogeneous mechanical properties.

According to the two-phase healing model, the bi-linear shape of the experimental reloading curves can mainly be attributed to the difference of the Young's modulus in the two different phases. This difference between the two numerical Young's modulus highlights the heterogeneity of the healed crack: some zones are healed with healing products with very good mechanical properties whereas other zones have very poor mechanical properties because they remain fractured.

The maximum bearing load obtained with the simulation is mainly influenced by the fracture energies assigned to both zones. Thus, the small experimental regain in bearing load could be explained by a lower fracture energy in the crack than in the undamaged zone. It leads to an easier recreation and propagation of a crack through the healed zone which has been reported in the experimental observation.

- 278
- 279 3.3.3. Comparison between numerical and experimental curves and
  280 evolution of the healing product properties

Numerical simulations were performed adjusting the height of the Zone 1 and the mechanical parameters of both zones in order to fit the experimental curves and obtain

283 information about the evolution of the healing product over time. The best fitting curves 284 were selected in order to reproduce the original stiffness and the maximum bearing load. These numerical curves were obtained with the parameters detailed in Table 2 and are 285 286 presented in Figure 8. On all the numerical curves, we can notice an overestimation of 287 the load corresponding to the end of the first initial slope followed by a small drop in 288 load. This is due to the two-phase model where the mechanical properties are not 289 continuous between the two phases. Regarding the material stiffness for the 'No healing' 290 case, numerical and experimental results cannot be compared. Although the mechanical model implemented here reproduce realistic decrease of stiffness and CMOD, it does not 291 reproduce the hysteretic behaviour creating the small recover in stiffness for the cracked 292 293 specimens due to friction between cracks lips.

The size of Z1 was increased with the healing time. This could indicate that, even if the hydration of the first clinker is very quick (first healing products are created within some hours), healing product is still created after some weeks in water. Thus, self-healing by further hydration could follow a 'surface controlled - diffusion controlled process' as described for the precipitation of calcite [15].

299 The mechanical properties inputted the two zones are different than the ones of the virgin 300 specimen. Young's modulus and fracture energy in Z1 are higher than the ones in the 301 virgin specimen. This could be explained by the better mechanical properties of pure C-302 S-H compared to the concrete. Also, we can notice that the fracture energy of Z1 increases 303 with time [36] which indicates that the healing product has a higher resistance to crack 304 propagation as the healing phenomenon progress. The mechanical properties affected to 305 Z2 are very low and consist well with the ones of an almost completely damaged zone 306 (Young's modulus close to 0).

308 4. Conclusions

309 In this study, a hydro-chemo-mechanical model for self-healing concrete was developed. 310 The localisation of the healed zone was investigated based on a diffusion-hydration 311 model. Regains in mechanical properties due to healing were assessed with a continuum 312 damage model. Based on the experiments and simulations, conclusions can be drawn as 313 follows:

- The mechanical properties of the healed crack are lower than the ones of the virgin
  material at a mesoscopic scale. This is explained by the partial healing along the
  crack which leads to a relatively small regain in bearing capacity after healing.
- The evolution of the mechanical properties of the healing product (Young's
  modulus, fracture energy) with time and the increase of its quantity over time
  explain the evolution of the mechanical properties of the concrete structure.
- Partial healing of cracks located around the zone in contact with water can be
   explained by the decrease of water flow with time due to the formation of healing
   products. The speed of formation of new hydrates in small cracks could be higher
   than the speed of the original hydration (with possibly no induction period).
- A relatively small healed zone with mechanical properties close to the virgin
   mechanical properties can lead to substantial regain in the structure mechanical
   properties (in autonomous healing solutions for example).

Modelling the autogenous healing in concrete is still a great challenge because it relies on the development of coupled models. Further investigations are needed to understand the recovery of mechanical and transport properties. In the future, numerical models may help to assist experimental observations and participate to predict the evolution of concrete structures properties during their service life.

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- 336

337	References

- K. van Breugel, Self-healing concepts in civil engineering for sustainable
  solutions: Potential and constraints, in: Proceedings of the Second International
  Conference on Self-Healing Materials, 2009.
- 341 [2] M. de Rooij, K. Van Tittelboom, N. De Belie, E. Schlangen (Eds), Self-Healing
  342 Phenomena in Cement-Based Materials, Springer Netherlands, 2013.
- 343 [3] C. A. Clear, The effect of autogenous healing upon leakage of water through344 cracks in concrete, Cement and Concrete Association (1985).
- 345 [4] N. Hearn, C. Morley, Self-sealing property of concrete experimental evidence,
  346 Materials and Structures 30 (7) (1997) 404–411
- 347 [5] H.-W. Reinhardt, M. Jooss, Permeability and self-healing of cracked concrete as
- a function of temperature and crack width, Cement and Concrete Research 33 (7) (2003)
  981 985.
- M. Li, V. C. Li, Cracking and healing of engineered cementitious composites
  under chloride environment, ACI Materials Journal 108 (2011) 333–340.
- 352 [7] S. Jacobsen, J. Marchand, L. Boisvert, Effect of cracking and healing on chloride
- transport in OPC concrete, Cement and Concrete Research 26 (6) (1996) 869 881.
- 354 [8] S. Jacobsen, E. J. Sellevold, Self healing of high strength concrete after
- deterioration by freeze/thaw, Cement and Concrete Research 26 (1) (1996) 55 62.

- Y. Yang, M. D. Lepech, E.-H. Yang, V. C. Li, Autogenous healing of engineered
  cementitious composites under wet-dry cycles, Cement and Concrete Research 39 (5)
  (2009) 382 390.
- K. Van Tittelboom, E. Gruyaert, H. Rahier, N. De Belie, Influence of mix
  composition on the extent of autogenous crack healing by continued hydration or calcium
  carbonate formation, Construction and Building Materials 37 (0) (2012) 349 359.
- [11] S. Jacobsen, J. Marchand, H. Hornain, Sem observations of the microstructure of
   frost deteriorated and self-healed concretes, Cement and Concrete Research 25 (8) (1995)
- 364 1781 − 1790.
- 365 [12] A. Neville, Autogenous healing: A concrete miracle?, Concrete international 24
  366 (2002) 76–81.
- 367 [13] Y. Abdel-Jawad, F. Dehn, Self-healing of self-compacting concrete, in: Fourth
  368 International RILEM Symposium on Self-Compacting Concrete (SCC 2005), 2005, pp.
  369 1023–1029.
- 370 [14] S. Granger, A. Loukili, G. Pijaudier-Cabot, G. Chanvillard, Experimental
  371 characterization of the self-healing of cracks in an ultra high performance cementitious
  372 material: Mechanical tests and acoustic emission analysis, Cement and Concrete
  373 Research 37 (4) (2007) 519 527.
- 374 [15] C. Edvardsen, Water permeability and autogenous healing of cracks in concrete,
  375 ACI Materials Journal 96 (4) (1999) 448–454.
- P. Pimienta, G. Chanvillard, Durability of UHPFRC specimens kept in various
  aggressive environments, in: Proceedings of the 10th International Conference On
  Durability of Building Materials and Components LYON [France] 17-20 April 2005.
- 379 [17] N. Ter Heide, Crack healing in hydrating concrete, Master's thesis, Delft
- 380 University of Technology (2005).

- [18] N. Ter Heide, E. Schlangen, Self healing of early age cracks in concrete, in:
  Proceedings of the First international conference on Self Healing Materials, Noordwijk
  aan Zee, The Netherlands, 18-20 April 2007.
- [19] H. He, Z.-Q. Guo, P. Stroeven, M. Stroeven, L. Sluys, Self-healing capacity of
  concrete computer simulation study of unhydrated cement structure, Image Analysis &
  Stereology 26 (2007) 137–143.
- 387 [20] H. He, Z. Guo, P. Stroeven, M. Stroeven, Numerical assessment of concrete's
- self-healing potential for promoting durability, International Journal of Modelling,
  Identification and Control 7 (2009) 142–147.
- 390 [21] Z. Lv, H. Chen, Modeling of self-healing efficiency for cracks due to unhydrated
- 391 cement nuclei in hardened cement paste, Procedia Engineering 27 (0) (2012) 281 290.

392 [22] Z. Lv, H. Chen, Self-healing efficiency of unhydrated cement nuclei for dome-

393 like crack mode in cementitious materials, Materials and Structures (2013) 1–12.

- 394 [23] H. Huang, G. Ye, Simulation of self-healing by further hydration in cementitious
  395 materials, Cement and Concrete Composites 34 (4) (2012) 460 467.
- 396 [24] H. Huang, G. Ye, D. Damidot, Characterization and quantification of self-healing
- 397 behaviors of microcracks due to further hydration in cement paste, Cement and Concrete
- 398 Research 52 (0) (2013) 71 81.
- 399 [25] P. Verpaux, T. Charras, A. Millard, Castem 2000: une approche moderne du
- 400 calcul des structures, Calcul des structures et intelligence artificielle (J.M. Fouet and P.
- 401 Ladevèze and R. Ohayon) (1988) 261–271.
- 402 [26] S. Fichant, Endommagement et anisotropie induite du béton de structures.
  403 modélisations approchées, Ph.D. thesis, Ecole Normale Supérieure de Cachan (1996).

- 404 [27] S. Fichant, C. La Borderie, G. Pijaudier-Cabot, Isotropic and anisotropic
  405 descriptions of damage in concrete structures, Mechanics of Cohesive-frictional Materials
  406 4 (4) (1999) 339–359.
- 407 [28] O. Bernard, F.-J. Ulm, E. Lemarchand, A multiscale micromechanics-hydration
  408 model for the early-age elastic properties of cement-based materials, Cement and
  409 Concrete Research 33 (9) (2003) 1293 1309.
- 410 [29] F. Grondin, M. Bouasker, P. Mounanga, A. Khelidj, A. Perronnet, Physico411 chemical deformations of solidifying cementitious systems: multiscale modelling,
  412 Materials and Structures 43 (1-2) (2010) 151–165.
- 413 [30] V. Picandet, A. Khelidj, G. Bastian, Effect of axial compressive damage on gas
  414 permeability of ordinary and high-performance concrete, Cement and Concrete Research
  415 31 (11) (2001) 1525 1532.
- 416 [31] A. Khelidj, M. Choinska, G. Chatzigeorgiou, G. Pijaudier-Cabot, Coupling
  417 between progressive damage, temperature and permeability of concrete : experimental
  418 and numerical study., Restoration of Buildings and Monuments 12 (2006) 299–316.
- 419 [32] M. Choinska, Effets de la température, du chargement mécanique et de leurs
  420 intéractions sur la perméabilité du béton de structure, Ph.D. thesis, Ecole Centrale de
  421 Nantes et Université de Nantes (2006).
- 422 [33] V. Picandet, G. Bastian, A. Khelidj, Compared imbibitions of ordinary and high
  423 performance concrete with null or positive water pressure head, Cement and Concrete
  424 Research 38 (6) (2008) 772 782.
- 425 [34] S. Granger, Caractérisation expérimentale et modélisation du phénoméne d'auto-
- 426 cicatrisation des fissures dans les bétons, Ph.D. thesis, Ecole Centrale de Nantes (2006).

- 427 [35] M. Matallah, C. La Borderie, O. Maurel, A practical method to estimate crack
  428 openings in concrete structures, International Journal for Numerical and Analytical
  429 Methods in Geomechanics 34 (15) (2010) 1615–1633.
- 430 [36] M. Matallah, M. Farah, F. Grondin, A. Loukili, E. Rozière, Size-independent
- 431 fracture energy of concrete at very early ages by inverse analysis, Engineering Fracture

- 432 Mechanics 109 (0) (2013) 1 16.
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	E <sup>(*)</sup>	$\nu^{(*)}$	$\mathbf{f}_{t}$	$f_c^{(*)}$	G <sub>f</sub>
	45 GPa	0.2	7 MPa	90 MPa	50 N/m
435	<sup>(*)</sup> From expe	rimental measur	rements		
436					
437					
438					
439	Table 2. Mechanical parameters input in the two-phase healing model				

## **Table 1.** Input mechanical parameters for the virgin specimen

Simulation	Sim 1 week	Sim 10 weeks	Sim 20 weeks
Crack width separation	8	7.5	7
Zone1/Zone2 (µm)			
E <sub>1</sub> (GPa)	60	60	60
F <sub>t1</sub> (MPa)	7.2	7.2	7.2
$G_{\mathrm{fl}}$ (N/m)	50	60	80
E <sub>2</sub> (GPa)	15	15	20
F <sub>t2</sub> (MPa)	7.2	7.2	7.2
G <sub>f2</sub> (N/m)	20	20	25





450 Figure 2. Flowchart of the model to study the impact of self-healing on mechanical

451 properties



460 experimental data from [14, 34].



Figure 5. Residual damage after 20 days of healing a) with normal diffusion and hydration parameters (residual damage close to 0 all along the crack), b) with increased

467 hydration (crack completely healed at its bottom part)



a)

Figure 6. Initial numerical crack width (in meter) (a) and two-phase healing model (b)





