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Modelling of autogenous healing in ultra high performance concrete

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The restoration of ultra high performance concrete (UHPC) specimens due to the self-healing phenomenon was investigated in this paper. A hydro-chemo-mechanical model based on micro-mechanical observations was established. The aim was to evaluate the mechanical properties of the new healing products in order to describe the partial recovery of the mechanical properties of healed concrete. An analysis of the influence of some physical parameters provided first explanations about the self-healing phenomenon. It was shown that the mechanical properties of CSH in the healed crack are lower than the ones of the virgin material.

1. Introduction

Although occurrence of cracks in concrete structures is taken into consideration during design, cracks generate important inspection and repairing costs. Some of them can seriously affect the durability and the stability of the structures. Thus, self-healing concrete could be a means to make important savings decreasing direct and indirect costs caused by repairing works [1,2]. It has been observed by many researchers that cracks in concrete can heal naturally, without any particular additive, under favourable conditions [3–11]. This phenomenon called 'autogenous' healing is the consequence of two main 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] and precipitation of calcium carbonate due to the reaction between calcium contained in the cementitious matrix with carbon dioxide dissolved in the water filling the crack [15].

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 cracks with an initial width up to around 200 μm [10]. Autogenous healing by further hydration has been studied by several researchers because of expected mechanical regains due to the creation of new calcium silicate hydrates (C-S-H). A global recovery of stiffness can be achieved by further hydration [16,18]. But, regains in compressive or flexural strengths have been found to be limited [8,10,14] because of relatively poor 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.

In this study, a hydro-chemo-mechanical model was developed to simulate autogenous healing by further hydration with the aim to explain the mechanical regains after healing and provide information about the self-healing product. Experimentally, Granger et al. [14] used ultra high performance cementitious material (UHPC) with a w/c ratio close to 0.2 to study the self-healing of small cracks with initials widths of 10, 20 and 30 μm. Mechanical properties of healed and uncracked specimens were compared at different stages (1 week, 3 weeks, 10 weeks, 20 weeks and 40 weeks). The hydro-chemo-mechanical model has been implemented in the finite element code Cast3M [25] to calculate the self-healing potential of a damaged concrete beam after cracking using three-point-bending test. Damage has been calculated by a modified microplane model [26,27]. Ingress of water has been simulated by the Fick's law and water interaction with the unhydrated cement particles led to their hydration considering a hydration model [28,29]. The recovery of mechanical properties of the cracked concrete beam was obtained by decreasing the local damage value due to the filling of empty spaces by new hydrates.

In the first part of this article, the relationships underlying the model will be explained into details and the model algorithm will be presented. Furthermore, the numerical results will be compared with experimental

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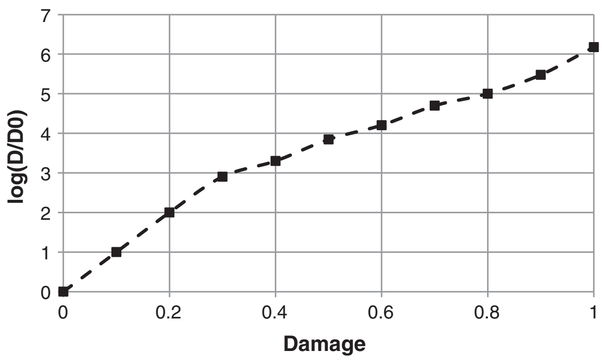

Fig. 1. Evolution of the diffusivity coefficient with local damage.

measurements and an analysis of the self-healing phenomenon will be suggested.

2. Description of the self-healing model

2.1. Problem formulation

The resolution of the global problem consists of 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: the displacements $\overline{U}_i$ are applied on the boundary Γ_i^u, the force $\overline{F}$ is applied on the boundary Γ^σ, and the velocity (or pressure, or concentration) is applied on the boundary Γ^C. The problems P1 and P3 are similar and lead to the calculation of the local displacement fields $(\overline{u}(\overline{y}))$, strain fields $(\overline{\overline{\varepsilon}}(\overline{y}))$ and stress fields $(\overline{\overline{\sigma}}(\overline{y}))$ as follow (where volume forces are negligible):

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

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

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

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

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

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

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

where $B_t = \frac{f_t}{\frac{G_f}{h} - \frac{f_t \cdot \varepsilon_{d_0}}{2}}$ represents a damage parameter to control the slope of the strain softening constitutive relation in function of the width h of the finite element and the fracture energy [36], $\varepsilon_{d0} = \frac{f_t}{E}$ the strain threshold and ε_{eq} the equivalent strain ($\varepsilon_{eq} = \sqrt{\overline{\overline{\varepsilon}}^e : \overline{\overline{\varepsilon}}^e}$ where $\overline{\overline{\varepsilon}}^e$ is the elastic strain).

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

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

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, and it fits the Poiseuille's law. The evolution of the diffusivity coefficient $D(d)$ is presented in Fig. 1.

$$\log(k) = (1-d)\log\left(k_p\right) + d\log(k_d) \qquad (8)$$

where $k_p = u^2/12$ is the permeability for damage close to 1 (u is the crack opening) and $k_d = k_0 \exp((\alpha D)^\beta)$ is the permeability for small damage values between 0 and 0.15 (k_0 is the initial permeability, α and β are two constants ranging respectively from 9.4 to 12.3 and from 1.4 to 1.6) [30].

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

$$\tau_i \frac{d\xi_i}{dt} = \widetilde{A}(\xi_i) \qquad (9)$$

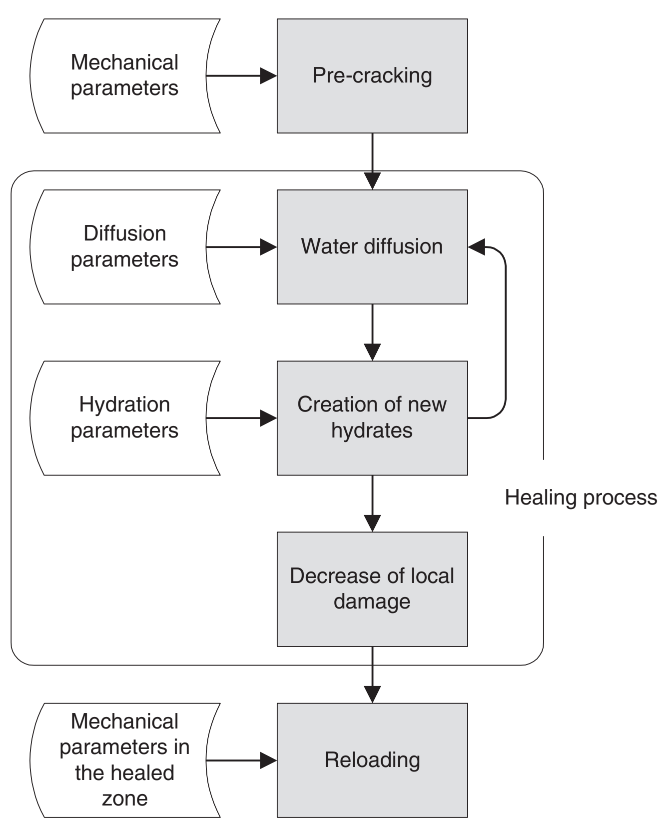

Fig. 2. Flowchart of the model to study the impact of self-healing on mechanical properties.