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Mechanical regains due to self-healing in cementitious materials: Experimental measurements and micro-mechanical model

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ABSTRACT

This paper focuses on mechanical regains that can be obtained due to self-healing of cementitious materials. Experimentally, small cracks with a width of around 10 μm were healed by water immersion and corresponding regains were assessed by means of three-point-bending tests. A general discussion about stiffness and strength regains is provided with the help of newly introduced indices. Besides, the first comprehensive finite element model to characterise the micro-mechanical properties of the healing products is introduced, based on the coupling of the microstructural hydration model CEMHYD3D and the finite element code Cast3M. The main objective is to analyse the healing potential and rate, as well as the nature of the healing products. The nature of the simulated healing products is in agreement with observation conducted using SEM/EDX on artificial cracks created at early age.

1. Introduction

Cracks in concrete generate massive inspection and repair costs. Self-healing of concrete could be a means to considerably decrease these costs by increasing impermeability and/or restoring mechanical properties of a damaged structure [1]. Concrete's intrinsic ability to heal, called autogenic healing [2], has been reported for many years and its discovery is attributed to the French Academy of Sciences. This natural process is being improved and supplemented for some years by promising engineered additions such as mineral additions [3], capsules containing healing agents [4–7], minerals producing bacteria [8–10] or fibres limiting the crack width [11–15]. Development of non-destructive monitoring techniques facilitates the assessment of self-healing efficiency, both for natural or engineered healing [16–19].

Two main mechanisms are considered predominant in autogenic healing: calcite or portlandite (CH) precipitation following calcium leakage into the crack, and further hydration triggered by water ingress into the crack [20,21]. These two mechanisms can occur together at the same time [22] but their extent likely depends on the age and composition of concrete (amount of anhydrous clinker) [23,24]. Further hydration and portlandite precipitation into the crack can lead to tensile strength regains [24], compression strength regains [25–27] and bending strength regains [28,29]. Stiffness regain can also be obtained at the same time [29]. Up to now, many studies show that mechanical regains are slow and immersion into water for several weeks is needed [29,30]. Moreover, most of the studies have been carried out on mature concrete, and did not investigate the healing potential of concrete cracked at early age while it can lead to better regains [24,31] and it could have practical implications concerning plastic or drying shrinkage cracks created some hours after setting. On the other hand, recent observations and models state that the healing phenomenon has a relatively high speed during the first dozens of hours [22,23], both for calcite and hydrate formation. However, the relative importance and the kinetics of these phenomena should be better understood in order to increase autogenous self-healing capabilities of concrete.

In order to develop autogenous healing and associated mechanical regains, numerical models could help design and optimise concrete's formulation. Several tools have been developed over the last decades to model microstructural evolution of concrete/mortar/cement paste over time from hydration to degradation. Modelling codes like CEMHYD3D simulating concrete hydration [32], can lead to good estimations of mechanical properties [33,34]. 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 [31,35,36], or to calculate the amount of healing product due to further hydration considering two crack modes [37,38]. Recently, a model simulating further hydration using water transport theory, ion diffusion theory and thermodynamics theory has been developed to determine the evolution of the filling fraction of cracks [22,39,40]. However, these models do not provide any information about the mechanical effects of self-healing. At a mesoscale, models assigning new properties to the healing products have been introduced

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through the use of lattice models [31,41] or interface elements [42]. A mesoscopic finite element model giving mechanical information about the distribution and the intrinsic properties of the healing products has been proposed [43] but does not provide a description of the self-healing development and its mechanical influence at a microscale, and there is a need for multiscale modelling from microscale [44] as for hydrating systems [45]. Regarding the limitations of the current models and the reproducibility of the experiments, coupled approaches, combining modelling and experimental work are useful to get a better understanding of the phenomenon.

Thus, to contribute to answering these questions, mechanical regains due to healing by ongoing hydration are investigated in this study using both experimental and modelling methods. Experimental works are conducted on specimens cracked at early age to investigate their healing potential according to various parameters (e.g. healing time, initial crack width and age at cracking). A focus is put on the minimum time to obtain mechanical regains for a given crack width in order to explain the development of the healing phenomenon. Also, the origin of the difference between stiffness and strength is investigated. Some SEM/EDX observations made on artificial planar cracked cement paste are presented in order to support the three-point bending tests results and give precise information concerning the nature of the healing products. Besides, a first micro-mechanical model for self-healing in cementitious materials is introduced. Healing by further hydration is simulated using our modified version of CEMHYD3D called CemPP to understand the kinetics and the potential of the healing phenomenon for different crack widths, age at cracking and healing period duration. The microstructure of healed specimens then served as input to the finite element code Cast3M [46] to monitor the mechanical regains and provide explanations for some experimental observations. This coupling has been made possible by extending the CEMHYD3D code to run different independent modules, each one providing part of the information necessary to the coupling with Cast3M, or directly operating on the microstructure.

2. Materials and experiments

2.1. Materials and sample preparation

Mortar was prepared with CEM II A-LL 42.5 R CE PM CP2 NF and 0/2 mm sand with the following proportions: 1250 kg/m^3 of sand, 755 kg/m^3 of cement, 265 kg/m^3 of water and a mass of superplasticizer (ChrysoFluid Optima 206, dry matter of 20%) representing 0.5% of the cement mass.

Mortar prisms with dimensions of $7 \times 7 \times 28$ cm^3 were cast. After 1 day of curing under sealed conditions in an air-conditioned room at a temperature of 20 °C, the specimens were demoulded (except the specimens cracked at 10 h which were demoulded at 10 h). A notch 7 mm deep and 5 mm wide was cut at the centre of all beams in order to initiate cracking at a specific location using three-point bending test. The specimens were then kept stored in tap water at a temperature of 20 °C before cracking and during the healing period. After the healing period, the healed and the reference specimens were reloaded after 2–3 h exposure to room temperature necessary for the Crack Mouth Opening Displacement (CMOD) dispositive preparation.

Complementarily, artificially cracked cement paste samples were prepared using the same cement to determine the extent and the composition of the healing products similarly to what has been done in [22]. The principal interest of this technique is that a precise distinction between the healing products and the original matrix can be obtained, which is not the case for post-observation of healed cement paste or mortar specimens containing realistic cracks. To prepare the samples, 2 parallelepipeds of cement paste with dimension of 15 mm × 15 mm × 30 mm were sawn and 2 adjacent faces with a length of 30 mm were polished using silicon carbide paper and diamond spray (down to 1 μm). In order to correspond to the cracking dates of the mortar specimens, artificial planar cracks with a width of around 20 μm were then created at the age of 1, 3 and 7 days by gluing 2 parallelepipeds together as illustrated in Fig. 1. Specimens were then immersed for 3 days to 4 weeks to heal. They were removed after the healing period and briefly polished on one of the initially polished sections before being investigated with SEM/EDX using an acceleration voltage of 20 kV ensuring a rather small penetration of the X-rays into the sample.

2.2. Quantification of mechanical regains due to healing

In order to evaluate the mechanical regains due to self-healing, specimens were pre-cracked, up to different levels of residual crack opening (CODi) employing the three-point bending test set-up controlled by CMOD. Some specimens were kept uncracked for reference. The real crack width was measured using an optical microscope at the bottom part of the beams as described in [16]. In this study, we focused on the influence of the age at cracking, the crack width and the healing time. A synopsis of the experimental programme is presented in Table 1.

After the healing period, the specimens subjected to healing were reloaded in order to determine their stiffness and their strength (resp. K_{healed} and F_{healed}). At the same time, the reference specimens of the same age were subjected to the three-point-bending test. A first load was applied to determine their initial stiffness and strength (resp. K_{ref} and F_{ref}), then they were unloaded to obtain the residual crack opening CODi defined for the healed specimens. The reference specimens were then reloaded immediately to determine their residual stiffness and strength (resp. $K_{unhealed}$ and $F_{unhealed}$) which could represent the parameters of unhealed specimens according to some studies [29,30]. The different quantities of interest are represented in Fig. 2. Several indices can be calculated to represent the healing efficiency, taking into account the brittle behaviour of the healed specimen [26]:

- K_{healed}/K_{ref} and F_{healed}/F_{ref} which can be compared resp. to $K_{unhealed}/K_{ref}$ and $F_{unhealed}/F_{ref}$,
- the index of load recovery with regard to the reference ILRref and the index of damage recovery with regard to the reference IDRref, which are similar to indices previously introduced [3]. These indices are defined by Eqs. (1) and (2). ILRref and ILKref vary between 0 (no healing) and 1 (perfect healing).

$$ILRref = \frac{F_{healed} - F_{unhealed}}{F_{ref} - F_{unhealed}} \quad (1)$$

$$IDRref = \frac{K_{healed} - K_{unhealed}}{K_{ref} - K_{unhealed}} \quad (2)$$

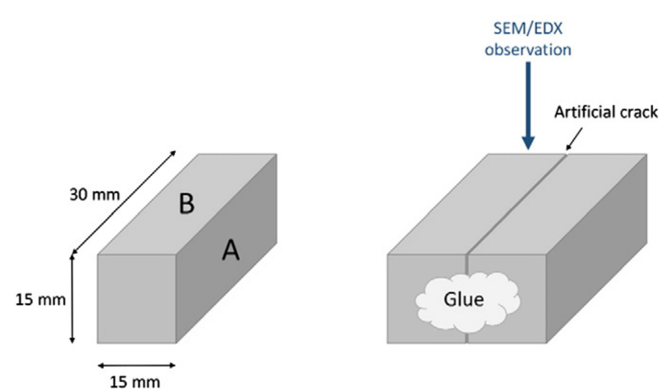

Fig. 1. Schematic diagram of the preparation on artificial cracks for SEM investigation. A and B denote the initially polished surfaces.