Mechanical regains due to autogenic healing in cementitious materials

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ABSTRACT

Concrete's intrinsic ability to heal, called autogenic healing, has been reported for many years. This natural process is being improved and supplemented for some years by promising engineered additions such as mineral additions, capsules containing healing agents, minerals producing bacteria, or fibres limiting the crack width. However, a deeper understanding of the natural phenomenon could help to design innovative healing solutions based on cementitious materials themselves.

In this study, self-healing potential of cementitous materials is studied both experimentally and numerically, modifying a hydration code (CEMHYD3D) and coupling it with a mechanical code (Cast3M). Experimental work, based on three-points-bending tests, has been conducted on specimens preferentially cracked at early age to investigate their healing potential according to various parameters (e.g. healing time, initial crack width, age at cracking and water-to-cement ratio). A focus is put on the minimum time to obtain mechanical regain for a given crack width in order to explain the development of the healing phenomenon and compare the results with the simulations.

Experimentally, small cracks with a width of around 10 µm can quickly heal within several days by immersion into water. Mechanical regain up to 80% of an uncracked specimen is observed for several water-to-cement ratios and is proportional to the initial crack width. The major influencing parameter is the age at cracking: when the crack is created after 72 h, the mechanical regain is considerably decreased and the healing period needs to be several weeks.

Numerical models can provide further information. The mechanical regain is due to the formation of bridges between the two cracks lips by ongoing hydration. According to the model, the major healing products in the crack are porlandite and calcium silicate hydrate.

1. INTRODUCTION

Concrete is very sensitive to crack formation but has an intrinsic healing ability. Two main mechanisms are considered predominant in autogenic healing: ongoing hydration of clinker nearby the crack triggered by water ingress, and calcite or portlandite precipitation following calcium leakage into the crack. Only the first phenomenon is assumed to produce mechanical regains. Up to now, many studies showed that mechanical regains are relatively slow and immersion into water for several weeks is needed [1]. But, the majority of these studies were conducted on mature concrete and did not consider early age cracks. Moreover, only few models were developed to provide information about the healing phenomenon in concrete. Recently, models were developed to understand self-healing phenomena at a micro-scale without mechanical characterization while some mesoscopic models were developed to investigate mechanical regains [2]. In this study, mechanical regains for specimens cracked at early age are investigated depending on various parameters (e.g. healing time, initial crack width and age at cracking). Numerical simulations were carried out using the hydration code CEMHYD3D (NIST) to understand the kinetics and the potential of the healing phenomenon for different crack widths, age at cracking and healing period duration. Then, the simulated microstructure functioned as input to the finite element code Cast3M to monitor the mechanical regains and provide explanations for some experimental observations.

2. EXPERIMENTAL MATERIALS AND METHODS

Mortar samples with dimensions of 7cm x 7cm x 28 cm were prepared with a water to cement ratio of 0.35. After 1 day curing in sealed conditions in an air-conditioned room with a temperature of 20°C, the specimens were demoulded. A notch with a depth of 1.5cm and a width of 5mm was created at the centre of the beam in order to initiate the crack. The specimens were placed again in water until the creation of the cracks. Specimens were cracked using crack mouth opening displacement (CMOD) controlled three-point-bending test until a real crack width of around 10µm. Then, they were immersed in tap water to obtain healing. After healing, the specimens were reloaded in order to quantify mechanical regains due to healing through the use of resistance and stiffness ratios in comparison with uncracked reference specimens.

3. NUMERICAL MODELLING

Microstructures were generated using CEMHYD3D with the use of a modified version of CemPy 0.15. The calculation volume has a size of 100 μm^3 with a discretization of 1 µm. Model hydration is carried out through the use of cellular automaton algorithms via cycles of dissolution, diffusion, and reaction, according to known reaction equations. Real particle size distribution of cement grains measured by laser diffraction is used as input to build the corresponding distribution in the model. At the same age as the real crack was created, a planar crack is created in the model. Then the constitution of the cement paste around the crack and the healing product are monitored as illustrated by Figure 1. After a given healing period, the phase constitution of a subvolume is imported in the finite element code Cast3M. Assuming linear elastic behavior of the various phases based on nano-indentation measurements, a homogenized tensile behavior is calculated. The mechanical regains are calculated through the use of the ratio Y_1/Y_2 where Y_1 and Y_2 are, respectively, the Young's modulus in the direction perpendicular to the crack and parallel to the crack. This ratio takes values from 0 when no healing occurred (no bridge between the crack lips) to around 1 for complete healing.

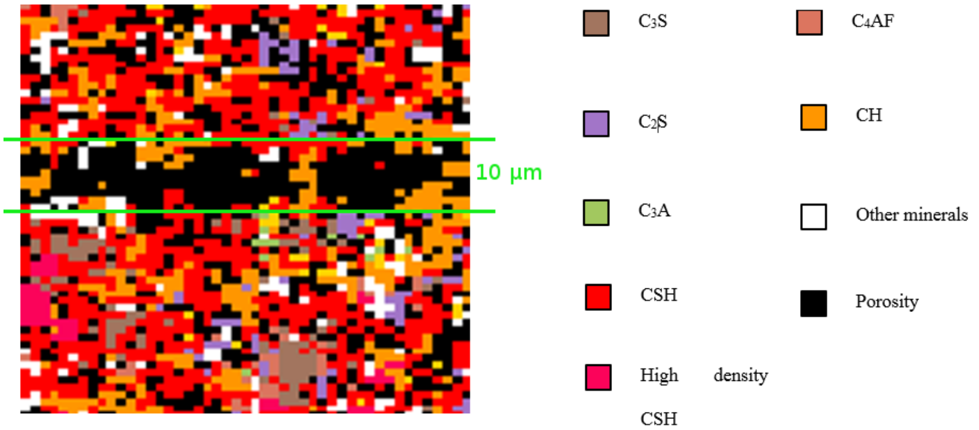

Figure 1: Numerical healing state after 126h of an initially 10µm wide crack.

4. RESULTS AND DISCUSSION

Experimentally, it has been observed that both resistance and stiffness regains can occur relatively fast within 2 weeks of immersion when the crack is created before 72 hours. Stiffness regains has been achieved on the majority of the specimens. However, resistance regains are mainly influenced by the age at cracking (see Figure 2): some specimens cracked at 24h exhibit maximal resistance up to 70-80% of uncracked specimens after 2-4 weeks of immersion, while resistance regains for specimens cracked at 7 days are limited after the same healing time. Initial crack width also influences the mechanical regains: the resistance ratio after 2 weeks of immersion for a 20µm wide crack is only 0.5 while it is 0.7 for a 10µm wide crack.
Numerically, the model reproduces the creation of bridges constituted of healing products into the crack. The analysis of the composition of the hydrates created into the crack reveals that portlandite is the major healing product along with CSH which corroborates other experimental results. Moreover, CSH remains located close to the crack lips because it grows nearby unhydrated particles while portlandite is present in the whole crack when healing occurs (see Fig. 1). Experimental observations are confirmed by the model as the age at cracking is crucial: for numerical 10µm wide planar cracks, only the one created at 24h lead to consequent mechanical regains ($Y_1/Y_2 > 0.5$) after 4 weeks of healing. For cracks created at 24h, healing products quickly precipitate into the crack within the first 50-100 hours. The model also shows that a rather good correlation, in terms of speed and initial starting date, can be made between the mechanical regains and the filling fraction evolution due to hydration products in the centre of the crack. Mechanical regains are quantifiable when the crack filling fraction is around 10% at approximately 50h, and, for longer healing periods, the mechanical regains are proportional to crack bridging

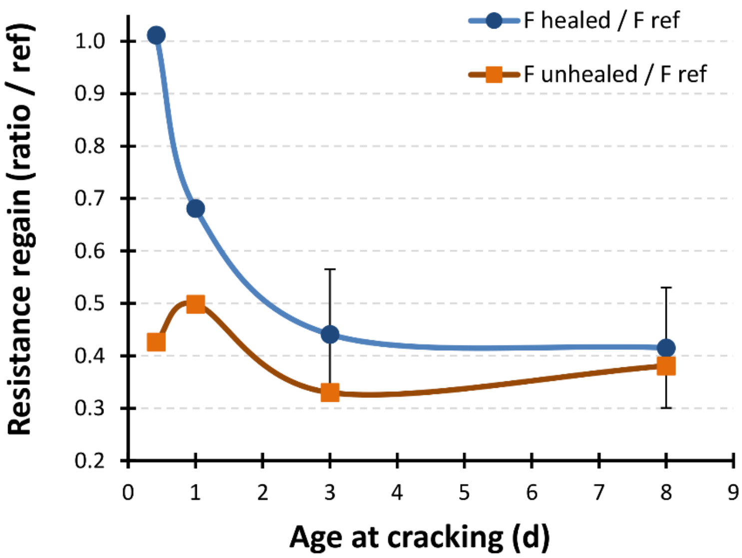

Figure 2: Influence of the age at cracking on the bending strength regain for specimens with a 10µm wide crack healed for 14 days.

5. CONCLUSIONS

In this study, autogenic mechanical regains have been studied both experimentally and numerically. Experimental analysis of three-point bending curves showed that very good mechanical regains can be obtained for early age cracking, both in terms of resistance and stiffness, while only stiffness regains are noticeable in case of later age cracking. A numerical hydration model has been adapted to simulate healing at a micro-scale and the output maps of the microstructure were imported in a finite element code. The homogenized properties of the microstructure confirmed the predominant role of the age at cracking and provided information about the nature of the healing products.

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