Non-destructive testing techniques for the observation of healing effects in cementitious materials – an introduction

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ABSTRACT

To develop an appropriate method of self-healing for cementitious materials including the right composition and amount of suitable healing agents it is required to investigate the healing efficiency for certain material mixtures. While some researchers evaluate the regain in compressive strength by means of destructive load tests, this method is obviously second best in particular for field applications. In a large EU project the best candidates among the non-destructive testing methods are investigated to be applied in small and large laboratory experiments as well as at real structures in-situ. The paper is giving an introduction to these techniques and addresses also issues of structural health monitoring used for example to monitor the healing effects on a long term basis and to assess the condition of the structure, where self-healing techniques are applied.

1. INTRODUCTION

Developing healing techniques for cementitious materials the self-healing efficiency should be evaluated to observe the usually time and space dependent healing effect. Up to now, the self-healing efficiency has mostly been evaluated based on the amount of regain in mechanical properties after a certain period. Most of the work done so far in this field is referenced in Van Tittelboom et al. (2012) and in the HealCon proposal (see below). While some researchers evaluate the regain in compressive strength, most evaluate the regain in strength, stiffness and/or energy when performing a tensile or bending test. Regain in mechanical properties is then determined by reloading the previously loaded and thus damaged sample and by comparing the mechanical properties gained during reloading at a certain time, with the original properties.
Non-destructive testing methods have – compared to this – obvious advantages. Granger et al. (2007) derived the amount of regain in energy due to autogenous crack healing from acoustic emission measurements. The authors conducted several acoustic emission experiments to evaluate the crack healing efficiency. In the case of Van Tittelboom et al. (2012) encapsulated healing agents were provided inside the matrix to obtain autonomous crack healing. With the used equipment it was not possible to prove crack healing by the released polyurethane-based healing agent, although capsule breakage was clearly noted from the captured acoustic events. Also

resonance frequency measurements have been proposed to evaluate the healing efficiency (Yang et al. 2009). This technique, however, has only been used when autogenous healing was the mechanism causing crack repair. Little information is available up to now about the regain of permeability properties related to cementitious materials working as a barrier against gases and fluids (air- and liquid-tightness). Nishiwaki et al. (2004) reported the use of a funnel which was glued onto the cracked surface to measure the water permeability at low water pressure. In Van Tittelboom et al. (2010) regain in water tightness is measured using a test setup based on the low pressure water permeability setup of Aldea et al. (2000) and Wang et al. (1997). Measurements at high water pressure were performed by Jonkers (2011) to evaluate the efficiency of bacterial self-healing concrete. The air permeability of cracked concrete has been measured by Yang et al. (2011).
In this paper we focus on the use of non-destructive testing techniques being applied to cementitious materials investigating either the effect of healing agents over time in laboratory experiments or to determine the healing efficiency in-situ at large structures. Before the individual techniques are addressed we want to describe one of the most developed technique with the potential of both, laboratory and in-situ applications.

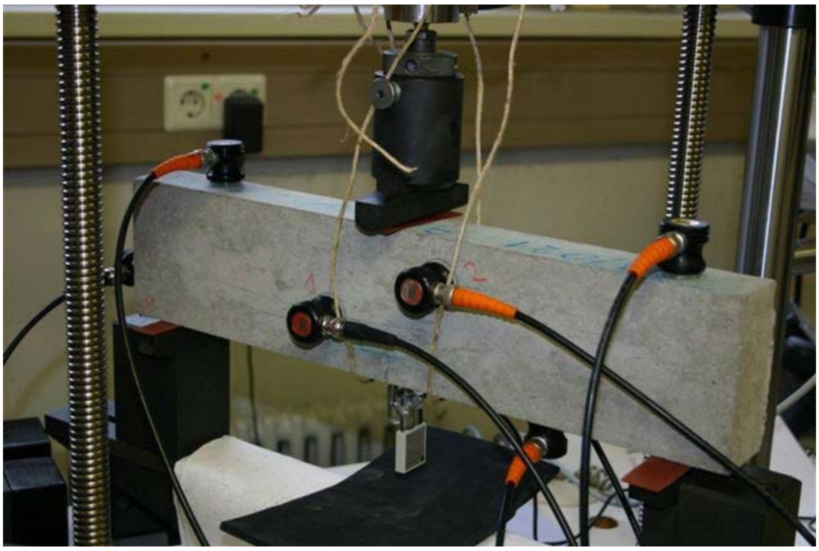

Fig. 1. Acoustic emission measurements during a crack width controlled three-point bending experiment at the University of Stuttgart to test self-healing efficiency (Van Tittelboom et al., 2012)

2. PREVIOUS ACOUSTIC EMISSION EXPERIMENTS

In a previous study experiments at the University of Stuttgart using acoustic emission (AE) techniques were conducted by Van Tittelboom et al. (2012). Acoustic emissions being released during a three-point bending experiment at concrete beams with polymer capsules as healing agents have been recorded by an 8-channel transient recorder and acoustic emission broadband transducers (fig. 1). The crack formation before and after healing has been recorded continuously during loading and unloading of the specimens and the events were localized in 3D (fig. 2). The signals (AE events) have been divided in arbitrarily chosen classes based on the AE events energy. It was supposed that AE events belonging to the highest classes were caused by capsule breakages. However, further research is needed to confirm this and eventually define more correct energy classes belonging to crack formation in the cementitious matrix, capsule breakage, reopening of previously healed cracks and so on. Optimization of the captured frequency range should also allow proving crack healing irrespective the type of used healing agent and the sample's size.

Figure 2: Acoustic emission activity recorded before (top) and after (bottom) healing of the specimen shown in fig. 1 (Van Tittelboom et al. 2012)

3. NDT METHODS

In a collaborative project called HealCon (Self-healing concrete to create durable and sustainable concrete structures) sponsored by the European Commission in the Seventh Framework Programme healing concepts for concrete structures are investigated. The project started January 2013. It is the aim of HealCon's Workpackage 7 to develop reliable and suitable non-destructive testing and monitoring techniques and combine existing ones to characterize the effects of different self-healing mechanisms in small and full-size specimens and to enhance the variety of non-destructive testing (NDT) techniques since a combination of methods has to be used to get reliable results. Responsible for this workpackage are the Technical University of Munich (first author) and the company SmartMote in Stuttgart, Germany (www.smartmote.de).
AE techniques alone will certainly not be sufficient. The range of applications from small to larger lab scale tests and up to real constructions requires different NDT approaches making the selection and combination of techniques more difficult. There are generally two ways NDT techniques can contribute. One is the observation of healing mechanisms and successes during mechanical loading. This will be done in small lab-scale, large lab or in field tests. The other is to assess the condition of the structure, where self-healing is studied. This is important for tests at a larger scale, while for smaller lab tests this is of minor interest since the composition and condition of the specimen is well controlled. In particular this is of interest also to offer real data about material properties for the numerical simulation.

The application of NDT techniques ranging from several centimeters over several meters to large structures with several tens or hundreds of meters will require techniques and measuring devices being capable to cover these scales, providing detailed and reliable data and being applied later in an economically efficient way concerning applications in the field. A first task will be the categorization and description of all potentially suitable non-destructive and monitoring techniques.
The NDT methods that are candidates to be used for monitoring of self-healing are:

a) Ultrasonic measurements in through-transmission and reflection
b) Acoustic emission techniques
c) Active Infrared-Thermography using thermally stimulated Lock-in techniques
d) Microwave and RADAR techniques
e) Resonance frequency measurements and modal analysis

Additional techniques are CT scanning, fiber optical measurement systems or displacement field mapping through Moiré fringes or optical image correlation. Measurements of e.g. strain, crack opening, temperature, humidity, electric impedance for salt and moisture determination can be integrated in small wireless sensor networks for long-term monitoring of large structures (Grosse et al. 2010).

The characterization of the specimens or structural components at each scale in regard to their mechanical properties can be done by ultrasound, microwave/Radar and vibration measurements. These methods will deliver information about the elastic moduli, the wave velocities, the permittivity and about other material properties necessary to be determined for numerical simulations. Some of these fundamental values are in addition essential to be determined prior to NDT applications.
Ultrasonic and vibration (modal) analysis methods can further on be applied to characterize the material properties in a more global way. Ultrasound transmission and reflection methods will help to evaluate the healing efficiency by the observation of changes of the velocity (compressional and shear), amplitude and frequency. They can characterize the healing efficiency by investigating changes of e.g. Young's modulus.
Infrared thermography, microwave/RADAR and in particular acoustic emission techniques can deliver detailed data about the healing process. AE techniques can basically be applied in small and larger lab tests to study the occurrence and distribution of micro-fractures during the experiments. Using 3D localization techniques enables for a spatial and time resolution observation of fracture processes. If possible, more sophisticated AE methods can be applied including moment tensor inversion techniques to distinguish between opening and shear fractures (Grosse and Ohtsu 2008). Data about the fracture type can help to separate cracks in the cement matrix from fractures of the tubes. However, AE techniques have limits being applied in the field. Infrared thermography can be used in an active lockin way to observe the healing efficiency by detecting the release of resin. Microwave and RADAR techniques are as well sensitive to fluids and are able to detect released resin in a shallow (microwave) or deeper (RADAR) area underneath the surface of a structure.
Neutron and X-ray radiography can provide useful information about the regain in tightness due to autonomous crack healing. It was proven that both can be used to visualize and discriminate between the capillary water uptake of untreated and autonomously healed cracks. However, a quantitative evaluation of the amount of water uptake was only possible when neutron radiography was used. Filling of the crack with healing agent and release of the agent from the capsules was visualized

using X-ray computed tomography (Van Tittelboom et al. 2011). However, in this study polyurethane was used as encapsulated healing agent and it seemed to be difficult to discriminate between cracks filled with polyurethane and empty cracks (filled with air).

4. MONITORING

Monitoring is usually used as either a repetitive measurement in more or less small time intervals or as a continuous monitoring technique. For a continuous monitoring, AE and vibration analysis techniques are qualified. Some physical quantities (e.g. moisture content, temperature, and strain or crack width) that are related to self-healing investigations can be monitored by sensor nodes measuring more or less continuously (Grosse et al. 2010). Using such a device usually several different sensors are combined and data processing is done directly in the node.

5. CONCLUSIONS

The above mentioned non-destructive test methods (and certainly some more) have the potential being employed to find out whether self-healing approaches are able to show repeated healing actions. Possibly several non-destructive techniques have to be combined to increase the reliability. Reliability can be further enhanced by the application of verification techniques, among them are radiographic CT scans. However, this is true only for experiments on the laboratory level. In the HealCon project it will be in particular investigated which potential each of the described techniques has to check the efficiency of healing.

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