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The efficiency of self-healing concrete using alternative manufacturing procedures and more realistic crack patterns

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ABSTRACT

During the last years, more and more research has been devoted to self-healing in cementitious materials. While most research is still done on carefully prepared small-scale mortar samples with predefined cracks, the healing efficiency should be investigated after exposure of the capsules to the concrete mixing and casting process and for random appearing cracks. In the current study, the resistance of brittle encapsulation materials, containing polyurethane, against the mixing and manufacturing process of concrete was studied. Different methods to protect the capsules were proposed and evaluated. In addition, realistic crack patterns were created in beams with embedded capsules. Non-destructive testing techniques such as digital image correlation, acoustic emission analysis and X-ray radiography were used to evaluate the survivability of the capsules upon mixing and the breakability of the capsules upon crack formation. Evaluation of the crack repair efficiency by performing water permeability tests showed some improvement in water tightness due to self-healing, but the water ingress into the cracks was not completely prevented.

1. Introduction

While more and more researchers investigate the possibility to build-in self-healing properties in cementitious materials using encapsulated healing agents, most experiments are still performed on carefully prepared small-scale mortar samples. Furthermore, to evaluate the efficiency, damage is concentrated in zones where the self-healing mechanism is intentionally incorporated. Obtaining autonomous crack healing in larger concrete elements where cracks appear at random locations, thus reducing the control on capsule breakage, is the next challenge. Up to now, examples found in literature remain limited to those stated in the next paragraphs.

Sun et al. [1] performed four-point-bending tests on concrete beams with dimensions of 100 mm × 100 mm × 400 mm which contained encapsulated cyanoacrylate while Tran Diep et al. [2] performed four-point-bending tests on even larger beams (125 mm × 200 mm × 2000 mm) containing encapsulated epoxy. Furthermore, Tran Diep [3] investigated the efficiency of his self-healing mechanism inside concrete columns (Ø 200 mm × 800 mm) and slabs (100 mm × 1000 mm × 1000 mm) damaged by horizontal loads and impact loads, respectively. In all his experiments, Tran Diep [3] used glass tubes as capsules which were protected by a mortar layer against impact of the aggregates during manufacturing. Dry [4–8] evaluated the self-healing efficiency of cementitious materials on frames (200 mm high, 400 mm wide, cross-section of 20 mm × 20 mm) with embedded tubes containing different types of healing agent depending whether the damping characteristics or the stiffness had to be regained. Cracks were created at the connections of the frames due to imposed horizontal displacements. Dry [5,9,10] also investigated the possibility to obtain autonomous crack healing in a real-scale concrete bridge deck (76 mm × 1220 mm × 6096 mm) by using adhesive-filled glass tubes. While part of the tubes were embedded below the surface deck to control the location of transverse shrinkage cracks upon creation of control joints, other tubes were mixed in by a truck mixer and served to repair shear cracks.

In each of the afore-mentioned studies, self-healing was evaluated as the ability to regain mechanical properties after crack formation. Even though it is more important that all cracks are sealed after the release of healing agent, to prevent ingress of aggressive substances, this was not evaluated. Only in the research of Kishi et al. [11], where concrete was casted in box shapes (inner dimensions 1000 mm × 1000 mm × 1000 mm, outer dimensions

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1200 mm × 1350 mm × 1600 mm), recovery of water tightness after impact was evaluated by filling the containers with water. However, in the research of Kishi et al. [11], self-healing was not related to the use of encapsulated healing agents, but to the inclusion of expansive agents which crystallize upon crack appearance.

The current paper describes the possibility of the earlier-published self-healing mechanism of the Magnel Laboratory for Concrete Research [12–14], comprising polyurethane encapsulated by glass or ceramic cylindrical capsules, to seal cracks appearing at random locations in concrete beams. Moreover, different mechanisms are investigated to protect glass or ceramic capsules against casting and concrete mixing.

2. Materials

2.1. Cylindrical capsules filled with healing agent

Due to the positive results obtained in previous experiments [12–15], a polyurethane-based healing agent (Meyco MP 355 1 K, BASF The Chemical Company) was selected for use. This product consists of two components; one is a prepolymer of polyurethane that starts foaming and expanding in moist surroundings, the second component is an accelerator that shortens the reaction time. Based on previous research [12], both, tubes made from glass and tubes made from ceramic, were used to encapsulate the healing agent. The ceramic tubes had an inner diameter of approximately 3 mm and a length of 60 mm. Also the glass tubes had an inner diameter of 3 mm and a length of 60 mm. However, for one test series, glass tubes with an inner diameter of 3 mm and a length of 400 mm were used.

Short capsules (60 mm) were filled with healing agent in the following way. One end of the tubes was sealed with methyl methacrylate (MMA). Then, the cylindrical capsules were filled with one of the components of the healing agent, which were injected by means of a syringe with a needle. While half of the amount of capsules was filled with the prepolymer of the polyurethane, the other half was filled with a mixture of accelerator (10 w%) and water. When all capsules were filled, the other free ends were sealed. Long tubes (400 mm) were filled with each component of the healing agent by placing them, with both ends open, in horizontal direction and by injecting the agent by means of a syringe with a needle. When all air inside the tubes was replaced by healing agent, both ends of the tubes were sealed with MMA while the tubes remained in horizontal direction to prevent the healing agent to leach out.

To enhance the probability that these brittle encapsulation materials would survive casting and possibly concrete mixing, two different methods were used to protect the short capsules [16]. In the first method, a cord was wrapped around the glass or ceramic capsules containing each component of the healing agent (Fig. 1A). By doing so, a rougher surface was obtained. Afterwards, a small layer of mortar (water-to-cement ratio of 0.5) was provided around these couples to protect them against impact forces of the aggregates (Fig. 1B).

The second mechanism consisted of a protection by cement paste bars (water-to-cement ratio of 0.4, Fig. 2). Moulds with dimensions of 10 mm × 10 mm × 80 mm were applied. First, a layer of cement paste was brought into the moulds. Subsequently, tubes filled with each component of the healing agent were juxtapositioned on top of it. After complete filling with cement paste, the specimens were vibrated. One day after casting, the samples were demoulded.

2.2. Concrete beams with(out) self-healing properties

Concrete mixes with the composition as shown in Table 1 were made to prepare the beams. The concrete compressive strength was measured on cores which were drilled from the beams at the age of 56 days. The mean compressive strength amounted to 58.6 N/mm^2, the standard deviation was 6.4 N/mm^2.

Moulds with dimensions of 100 mm × 100 mm × 650 mm were used to cast the concrete beams with and without self-healing properties. In addition to steel fibres (RC-80/60-BP) with a diameter of 0.71 mm, which were added to the concrete mix, each beam was reinforced with two steel bars with a diameter of 6 mm which were provided at a height of 10 mm.

For beams belonging to the reference test series (REF, Table 2), moulds were filled with plain concrete in one step and vibrated on a vibrating table.

For the test series containing short (60 mm) or long (400 mm) capsules without protection (GLA_L_W, GLA_S_W and CER_S_W, Table 2), moulds were filled with concrete in two subsequent steps. First, a concrete layer of around 10 mm was applied. Then, capsules were attached to steel wires which were wrapped around the reinforcement bars as shown in Fig. 3A and B. All tubes were positioned aligned with the reinforcement bars and concentrated in the middle zone. After positioning all capsules, the moulds were further filled with concrete.

For the test series where glass or ceramic tubes surrounded by a mortar layer were used (GLA_S_M and CER_S_M, Table 2), capsules were placed at the bottom of the mould. Again capsules were aligned with the reinforcement bars and concentrated in the middle zone (Fig. 3C). Beams of this test series were filled with concrete in one step. Due to subsequent vibration, the capsules would rise a few millimetres from the bottom of the mould and would be positioned in the lower layer of the beams.

Samples belonging to the last test series (GLA_S_C and CER_S_C, Table 2) were again moulded in two phases. Half of the concrete mix used to cast these beams was mixed once more to distribute the capsules embedded in cement paste bars. For the first sample, mixing was done using the concrete mixer, however, as half of the capsules seemed to be broken after mixing, for the remaining sample of this series, mixing in of the capsules was performed by hand. The concrete mix containing the encapsulated healing agent was first poured into the moulds. Subsequently, the other half of the

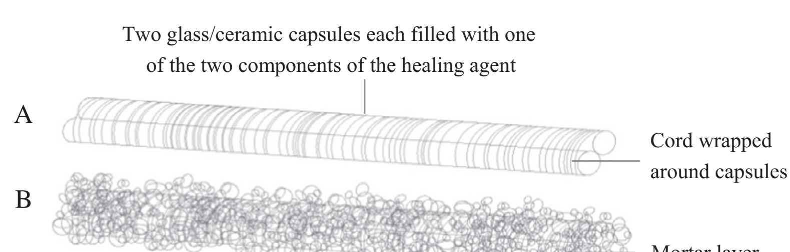

Fig. 1. Protection of the short glass and ceramic capsules by winding them with a cord (A) and providing a tiny mortar layer (B).