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Comparison of different approaches for self-healing concrete in a large-scale lab test

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HIGHLIGHTS

- Both approaches have potential to be applied in real-scale concrete structures.
- Use of encapsulated PU requires more preparation compared to the addition of SAPs.
- One approach is triggered through crack appearance the other by water ingress.
- SAPs resulted in the highest healing efficiency based on crack width measurements.
- Release of PU from the capsules and crack closure was clearly noticed from CT.

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ABSTRACT

After several years of research in the Magnel Laboratory for Concrete Research (Belgium) to obtain concrete with self-healing properties, two of the most promising mechanisms were tested on a larger scale. One mechanism is based upon the encapsulation of polyurethane which is embedded in the matrix. Self-repair is obtained when crack creation causes capsule breakage, release and subsequent hardening of the polyurethane inside the crack. The second approach relies upon the addition of superabsorbent polymers (SAPs) to the concrete. These SAPs take up water entering via the crack, swell and block the crack. In addition, when they release their water content later on, they induce continued hydration and calcium carbonate precipitation. Real-scale concrete beams (150 mm × 250 mm × 3000 mm), with and without self-healing properties, were made and the self-healing efficiency was evaluated after crack creation by means of four-point bending. Based on the measured crack width reduction over time, it was shown that improved autogenous crack healing was obtained when superabsorbent polymers were added to the mixture. From the acoustic emission analysis, the proof of glass capsule breakage upon crack formation was obtained. X-ray tomography, fluorescent light microscopy and thin section analysis demonstrated that cracks were indeed partially filled with hydration products, calcium carbonate crystals and/or polyurethane which leached from the broken embedded capsules. Although it would be expected from both findings that this would result in a decrease of water ingress into the healed cracks, this could not be proven within this study.

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1. Introduction

As concrete is a frequently used construction material but as it is susceptible to crack formation, which reduces the durability and increases the maintenance costs, self-repair of cracks in concrete is nowadays a very popular research topic. It was actually in 2001, when White et al. [1] published their paper in Nature about self-healing in polymer-based materials, that research on the development of self-healing materials gained a real boost and that attempts were taken to implement self-healing properties inside cementitious materials. In fact, concrete also possesses a kind of natural ability to repair damage to a certain extent [2]. If water enters into a crack and gets into contact with unhydrated cement particles, these can further hydrate resulting in crack closure. If both water and carbon dioxide enter, crack closure can be obtained through the precipitation of calcium carbonate particles from leaching calcium hydroxide. However, as the natural, named autogenous, crack healing mechanism is limited to small cracks [3], many attempts have been made to engineer concrete in order to obtain an improved, autonomous, crack healing efficiency.

Some approaches rather promote the autogenous crack healing ability by limiting the crack width through the addition of synthetic fibers [4] or by the use of shape memory alloys [5] which return to their original shape, and thus result in crack closure, upon heating. Other approaches promote the autogenous sealing and/or healing ability by providing an extra amount of water through the use of superabsorbent polymers (SAPs) [6–9]. SAPs take up water entering the cracks, swell and block the cracks against ingress of aggressive liquids. During dry periods, SAPs slowly release the absorbed water and provide it for further hydration and calcite precipitation. In other approaches, calcite precipitation is intensified by the addition of calcium carbonate precipitating micro-organisms to the matrix [10,11]. Upon water ingress via the cracks these organisms start to consume available nutrients and precipitate calcium carbonate to close the crack. Next to these self-healing approaches, capsule-based [12,13] and vascular-based [14,15] mechanisms are reported, in which autonomous crack repair is obtained by release of a, mostly polymer-based, healing agent from embedded capsules or from a vascular system. Release of the agent is triggered through breakage of the capsules or the vascular system at the moment of crack formation.

We, in the Magnel Laboratory for Concrete Research (Belgium), started our research on self-healing cementitious materials in 2008. A number of the above-mentioned self-healing approaches have been investigated on lab-scale, resulting in diverse self-healing efficiencies. For this study, two of the most promising approaches were selected to be applied and tested on their efficiency on a larger scale.

2. Materials

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

The efficiency of two different self-healing approaches was compared in this study; self-healing by encapsulated polyurethane and self-healing through inclusion of superabsorbent polymers (SAPs). To prepare the beam where self-healing was obtained by release of polyurethane from embedded capsules (Table 1, PU), glass capsules were filled with the selected healing agent. About 350 glass capsules with a length of 50 mm and an inner and outer diameter of 3 mm and 3.35 mm, respectively, were first sealed with methyl methacrylate (MMA) at one end. Subsequently, the healing agent was injected into the tubular capsules by means of a syringe with a needle. In this study, a one component polyurethane-based healing agent, which was developed within the framework of this study, was applied. This agent hardens upon contact with humidity inside the concrete matrix. After filling of the capsules with healing agent, the other end was sealed with MMA glue. To position the capsules within the mould of the beam, a network of plastic wires was connected with the walls of the mould at a depth of 10 mm. Every 40 mm over the complete length of the mould, except the outer 160 mm, a wire connected one side of the mould with the other (Fig. 1A). Glass tubes were glued onto this network of wires by means of MMA glue. Each time five capsules were placed with an intermediate distance of 46 mm and at both capsule ends there was 5 mm overlap with the wires. The next row was then arranged in an alternating way compared to the previous row (Fig. 1B). Next to the network of capsules, this mould contained four reinforcement steel bars with a diameter of 10 mm. These were positioned underneath the network of capsules in order to obtain a concrete cover on top of the bars of 20 mm. In this way the network of encapsulated healing agent was positioned in the middle of the concrete cover layer and ingress of aggressive substances towards the reinforcement via cracks within the concrete cover could be avoided when the self-healing mechanism is properly activated due to crack formation.

For the second self-healing approach under investigation, being the use of SAPs to cause crack sealing and promote autogenous crack healing (Table 1, SAP), no additional preparation was needed compared to the reference beam (Table 1, REF), as the SAPs are added dry to the concrete upon mixing. The SAPs used within this study were cross-linked copolymers of acrylamide and acrylate which were obtained through bulk polymerization and have particle sizes below 600 μm. The SAPs have an absorption capacity of 308.2 ± 4.7 g/g SAP in de-ionized water and 37.9 ± 1.6 g/g SAP in cement filtrate as determined by means of the filtration method. For the SAP beam, similar as for the REF beam only the four reinforcement bars were placed into the moulds beforehand (Fig. 1C). For these beams, similar as for the PU beam, the reinforcement bars were positioned in such a way that the concrete cover on top of them amounted to 20 mm.

Depending on the self-healing approach under investigation, concrete batches with slightly different properties were prepared to make the concrete beams. As vibration with a needle would not be possible for the PU beam, due to the network of wires with capsules, it was chosen to use self-compacting concrete (SCC) for all beams. The composition of each of the concrete mixes is shown in Table 2, together with the flow, air content, density and strength of the concrete. All components were mixed in a 200 L mixer. The mixing procedure was as follows: sand, gravel, cement, limestone filler (and dry SAPs) were mixed properly and homogenously. Subsequently, the needed amount of water was added under continuous mixing. After 1 min of mixing polycarboxylate superplasticizer (concentration 35%) was added steadily while mixing persisted. Fresh concrete properties such as flow, air content and density were measured for each mix immediately after the mixing procedure was finished. Subsequently, the moulds were filled. While part of the concrete mix was used to fill three 150 mm side cubes for determination of the density of the hardened concrete and 28-day compressive strength, most of it was used to fill the moulds of the beams having dimensions of 150 mm × 250 mm × 3000 mm (150 mm is beam height, 250 mm is width of the beam). While the moulds of the cubes were placed in an air conditioned room (temperature 20 ± 2 °C, >90% relative humidity), the moulds of the beams were covered with plastic foil after casting and stored in a standard laboratory climate. Cubes were demoulded after one day and the moulds of the beams were removed after 6 days. After demoulding, cubes and beams were restored, respectively, in the air conditioned room (temperature 20 ± 2 °C, >90% relative humidity) and in the laboratory until the time of testing.

3. Methods

3.1. Four-point bending test

In order to create multiple cracks in the concrete beams, they were loaded in four-point bending. To simplify performance of the water ingress measurements (see Section 3.3), beams were loaded in upward direction (Fig. 2). The metal rollers, used to exert the line loads, were placed symmetrically with regard to the middle of the beam and with a distance in between of 1000 mm. The rollers, representing the supports, were positioned at the ends of the beam. For one of both supports the displacement was fixed in all directions, while the other one was positioned in such a way that movement in x-direction was possible. To make sure that the exerted load was exactly the same for each loading roller and that the load increased at the same speed for both rollers, one jack was used and the force exerted by this jack was transmitted to both rollers by means of a metal beam (Fig. 2). The exerted force

Table 1
Approaches under investigation.

Description	Code
Reference beam without self-healing properties	REF
Beam containing encapsulated polyurethane	PU
Beam containing super absorbent polymers	SAP