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Bacteria-based self-healing concrete to increase liquid tightness of cracks

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HIGHLIGHTS

- Sealing efficiency of cracks was studied on bio-based self-healing mortar specimens.
- Wet-dry healing treatment favoured the sealing efficiency in bio-based samples.
- Bacterial activity was proven through ESEM observations and O_2 profile measurements.

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ABSTRACT

The innovative technology of self-healing concrete allows the material to repair the open micro-cracks that can endanger the durability of the structure, due to ingress of aggressive gasses and liquids. Various concepts of self-healing concrete have been developed, with target on the recovery of water tightness after cracking. Among those, bacteria-based self-healing concrete has shown promising results regarding the improvement of crack sealing performance. In this study, the bacteria-based healing agent is incorporated into lightweight aggregates and mixed with fresh mortar. By this means, autogenous healing of concrete is enhanced and upon cracking the material is capable to recover water tightness. The study focuses on the investigation of the effect of healing agent when incorporated into the mortar matrix and the evaluation of the recovery of liquid tightness after cracking and exposure to two different healing regimes (water immersion and wet-dry cycles) through water permeability tests. It was found that the compressive strength of the mortar containing lightweight aggregates is not affected by the presence of the healing agent. The study also reveals that the recovery of water tightness does not differ substantially either for specimens with or without healing agent when immersed continuously in water. Conversely, the recovery of water tightness increases significantly for specimens containing the healing agent compared to specimens without it, when subjected to wet-dry cycles. Oxygen concentration measurements and bacterial traces on calcite formations confirmed the bacterial activity on specimens containing the healing agent.

1. Introduction

Concrete is a structural material that has been widely used in the modern age [1]. Yet, unavoidable surface micro-cracking can increase the permeability, make it susceptible to aggressive agents and consequently affect the durability of the material [2–4]. Cracking of concrete structures is triggered by temperature and humidity fluctuations, mainly at an early age, and by external loading, mainly at a later age, creating a pathway through which harmful substances enter into the material and decay it gradually over time [4].

It is known that fine cracks, exposed to moist conditions can sometimes close completely [5]. This property, namely autogenous healing, allows the crack to seal through chemical, physical and mechanical processes that take place inside the crack [6]. The mechanisms that cause “crack closure” or “crack bridging” have been known through previous studies [6–8]. However, the most significant factor that influences the autogenous healing is the formation of calcium carbonate ($CaCO_3$) [6]. Scientists more than a decade have worked on various self-healing concrete concepts [4,5], in order to enhance the autogenous healing of concrete. Among the most popular concepts are those which: a) limit the crack width by incorporating fibres [9–13], b) expand the cement matrix when in contact with water by using hydrogels [14,15], c) introduce a healing agent that is activated

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and released upon cracking [16–24] and d) combine the previous [10–12,25–28].

Recently, bacteria-based self-healing concrete has drawn a lot of attention. The bacteria-based healing agent consists of bacterial spores and organic compounds incorporated into the concrete matrix. The healing agent is encapsulated, in order to immobilize and protect it from crushing during mixing and from the high alkalinity of the cement matrix [16].

In the current study, the bacteria-based healing agent is embedded into lightweight aggregates (LWA). Upon crack formation the weak lightweight capsules break; the healing agent activates and fills the open crack by precipitating $CaCO_3$. Although crack closure can be characterized through visual observations [16,29–31], the functional property of a self-healing material, i.e. the ability to seal the crack and regain water tightness, must be investigated differently. In order to assess the recovery of water tightness (RWT) after cracking and healing, various studies [6,9,29,30,32–33] have developed several crack permeability tests. The aim of this study is to investigate how the addition of the healing agent affects the fresh- and hardened-state properties of the mortar and to evaluate the RWT after cracking and healing through two different healing treatments (water immersion and wet-dry cycles).

2. Materials and methods

2.1. Preparation of the healing agent

The bacteria-based healing agent consisted of spores derived from alkaliphilic bacteria of the genus *Bacillus* and organic mineral compounds. The healing agent is incorporated in LWA (expanded clay particles, Liapor 0/4 mm, Liapor GmbH Germany) via an impregnation under vacuum with calcium lactate (200 g/L), yeast extract (4 g/L) and bacteria spores (10^8 spores/L) solution. Following the impregnation, the LWA were dried for approximately for 5–6 days at standard at temperature (20 ± 2 °C) with (60 ± 10) % RH, until a constant weight was achieved. After drying, the impregnated LWA showed weight increase of approximately 10% [34], comparing to their initial dry weight.

2.2. Preparation of the mortar specimens

Three types of mixtures were investigated. One reference mixture (REF) with normal weight aggregates, one control mixture (CTRL) with non-impregnated LWA and one mixture (B) with impregnated LWA. The mixtures contained ordinary Portland cement (CEM I 42.5 N, ENCI, The Netherlands) and 0/4 mm sand or 0.125/1 mm sand and 1/4 mm LWA. The detailed mixture proportions are presented in Table 1. For the examination of the influence of the healing agent on the fresh- and hardened-state properties of the mortar 9 prisms (40 mm × 40 mm × 160 mm) were cast per mixture. In addition, for the investigation of sealing efficiency of the mortar mixtures, 15 reinforced mortar prisms (40 mm × 40 mm × 160 mm) modified with a hole in their centre, as seen in Fig. 1, were cast per mixture. All specimens were demoulded 24 h after casting and kept in a room with standard temperature (20 ± 2 °C) and >95% RH for 28 days.

2.3. Material characterization, crack introduction and healing on mortar specimens

Immediately after mixing, three fresh-state mortar properties were tested, i.e. consistency, bulk density and air content. The tests and the values obtained were according to EN 1015-3, EN 1015-10 and EN 1015-7 respectively. Flexural and compressive strength was determined on 3-days-, 7-days- and 28-days-old (unreinforced) specimens according to the procedure described at EN 1015-11.

Table 1
Mortar mix designs.

Mixture	CEM I (kg/m^3)	Water (kg/m^3)	0.125/1 mm Sand (kg/m^3)	1/4 mm Sand (kg/m^3)	1/4 mm LWA (kg/m^3)
REF	463	231.5	855	825	0
CTRL	463	231.5	855	0	257
B	463	231.5	855	0	280[1]

[1] This weight includes the weight of impregnated healing-agent into the pores of the LWA.

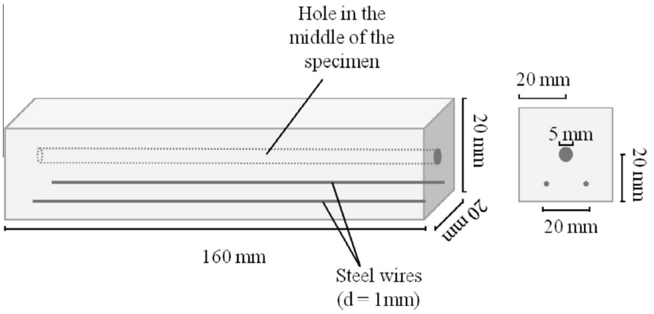

Fig. 1. Specimens for evaluation of RWT.

Damage introduction was performed on 28-days-old reinforced prismatic specimens via 3-point-bending test (Fig. 2). The specimens were loaded until the formation of a single stable and rather large crack (350 μm), without being fractured completely into two parts. Each specimen was placed on the testing machine, where a vertical load was applied at the middle span of the sample, so that the crack opening increased constantly by 0.5 μm/s. When a crack opening of approximately 400 μm was reached, the samples were slowly unloaded. After unloading, the crack width was reduced to approximately 350 μm.

Following the crack creation, 6 specimens of each mixture were placed horizontally in a plastic container filled with tap water for crack healing. The specimens were placed on the top of spacers (10 mm high), so that there was space between them and the bottom of the container. The container was kept open to the atmosphere at standard room temperature (20 ± 2 °C) with (60 ± 10) % RH for 28 or 56 days. Extra water was added (on a weekly basis), to keep a constant liquid-to-solid ratio. Another 6 specimens of each mixture were subjected to wet and dry cycles for 28 or 56 days. The specimens were placed on spacers in plastic containers. Each cycle lasted 12 h. An external pump was either supplying the container with water or was removing it. The container was kept open to the atmosphere at standard room temperature (20 ± 2 °C) with (60 ± 10) % RH.

2.4. Crack water permeability test

The sealing efficiency of the healing agent was initially investigated through stereomicroscopic images. Although stereomicroscopic observations can give an indication, the results should be combined with a crack permeability test in order to link the functional property (water permeability) with the visual observations. The test was performed on three specimens before; and on another three specimens after the healing treatment, according to [33]. Before performing the permeability test and after the healing treatment was completed, one of the two end-sides (40 mm × 40 mm) of the sample was covered with a glue layer to prevent water passage from this side.

Under the crack an electronic scale connected with a computer was recording the weight of the water dripping from the crack as a function of time. Each test lasted approximately 10 min, in order to make sure that the water flow out of the crack was stable. After the completion of the crack permeability tests, the RWT for each set of the three healed specimens was calculated as follows:

$$RWT = \frac{W_{n-h}(t) - W_h(t)}{W_{n-h}(t)}\ x\ 100\% \qquad (1)$$

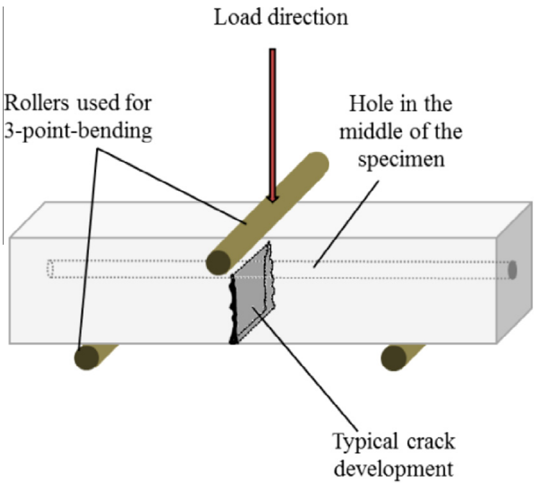

Fig. 2. Three-point-bending set-up.