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Development and application of bacteria-based self-healing materials

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Henk Jonkers, joined in 2006 the department of Materials and Environment of the Faculty of Civil Engineering and GeoSciences of the Delft University of Technology to work together with Erik Schlangen within the framework of the Delft Centre for Materials (DCMat) on the development of bacteria-based self-healing concrete. Other interests and currently running research projects concern the development and application of bio-based products and processes to mitigate environmental impacts of civil engineering practices.
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ABSTRACT: In 2006 a research program was launched at Delft University of Technology aiming for the development of a new class of materials, i.e. materials with an inbuilt healing mechanism. The idea is that these novel materials can self repair damage resulting in substantially decreased maintenance and repair costs and increased service life. Several research projects focus on cement-based materials such as concrete and asphalt. One project that will be discussed here concerns bacterial-based concrete. The bacteria which are added to the concrete mixture are able to produce calcium carbonate-based minerals, a process that can result in sealing and water tightening of cracks. These and more examples show that novel materials and constructions which are designed to control damage rather than prevent damage by featuring an inbuilt healing mechanism could be more economical than traditional ones.

Keywords: Self healing concrete, bacteria, crack repair, sealing

INTRODUCTION

Concrete is a strong and relative cheap construction material that is basically composed of water, cement, sand and gravel, and contains for most structural applications a steel reinforcement. Concrete can therefore be considered to represent a composite material. Different types of damage can generally occur in composite materials. In concrete two main types of damage can be recognized. One is related to 'structural' damage, i.e. damage that hampers the structural integrity of a construction. In this case the steel reinforcement is usually affected, either due to corrosion or impact overloading. Strength of the construction is in this first type of damage thus usually affected. The second type of damage in concrete is more related to degradation processes of the matrix material. Micro-cracking and other damaging processes which strongly increase the permeability of the concrete matrix result in durability problems which are related to decrease in service life rather than immediate strength problems. Damages of the second category cause problems such as leakage and increased ingress rates of harmful substances such as chloride and carbon dioxide, what could result in accelerated corrosion of the embedded steel reinforcement.

Manual repair of damaged concrete is the traditional solution to restore strength or increase the service life of constructions. However, since about two decades the possibility to make use of self-repair features of concrete or even specifically implement a self-healing system into concrete constructions is considered by scientific researchers. It was e.g. recognized in the past that most types of concrete feature some crack-sealing potential. It was observed that crack ingress water can activate partially- or non-hydrated cement particles present on crack surfaces which due to hydration can bridge cracks resulting in reduced permeability or even complete sealing of micro-cracks. This type of so-called 'autogenous' healing has been reviewed by e.g. [1-3]. Autogenous healing results thus particularly in sealing of cracks, a process that not necessarily results in strength increase but rather in leakage prevention of water retaining structures such as reservoirs. Several researchers in subsequent years attempted to increase the potential of self-healing properties in concrete by incorporating a specific mechanism in the concrete. Specifically in order to regain strength e.g. Ter Heide et al. [4] and Granger et al. [5] studied the effect of increased binder content in concrete mixture compositions. Incorporating a specific mechanism in concrete with the aim to enhance its self-healing properties clearly surpasses autogenous healing, and Schlangen and Joseph [6] therefore classified such healing systems as 'autonomous'. Examples of specially designed autonomous self-healing concretes are those with inbuilt encapsulated sealants or adhesives [7], special fibers or tubes used for storage of chemicals [8-13], incorporation of specific expansive components which upon coming into contact with moisture expand thereby filling voids and cracks [14, 15]. Another special case represents the usage of specific mineral-producing bacteria which increase the density of the concrete matrix and seal occurring micro-cracks [16-19].

One specific type of self-healing concrete currently under development at the Delft University concerns concrete featuring inbuilt mineral-producing bacteria. Objective in this case is development of autonomous crack-sealing concrete to increase durability and service life of constructions.

BACTERIA-BASED SELF-HEALING CONCRETE

In past studies the use of bacteria for cleaning concrete surfaces or for upgrading damaged limestone monuments or porous concrete surfaces was investigated [20]. In 2006 we started in Delft a research project aiming to use bacteria as a component of a self-healing agent for incorporation in concrete where it could act as an autonomous repair system. In a series of studies it was subsequently found that a specific group of spore-forming alkali-resistant bacteria of the genus *Bacillus* shows mineral-producing activities even when incorporated for prolonged periods in concrete [17, 21-22]. The principle mechanism of bacterial crack healing is that the bacteria themselves act largely as a catalyst, and transform a precursor compound to a suitable filler material. The newly produced compounds such as calcium carbonate-based mineral precipitates should than act as a type of bio-cement what effectively seals newly formed cracks. Thus for effective self healing, both bacteria and a bio-cement precursor compound should be integrated in the material matrix. Bacteria that can resist concrete matrix incorporation exist in nature, and these appear related to a specialized group of alkali-resistant spore-forming bacteria (see Figure 1).

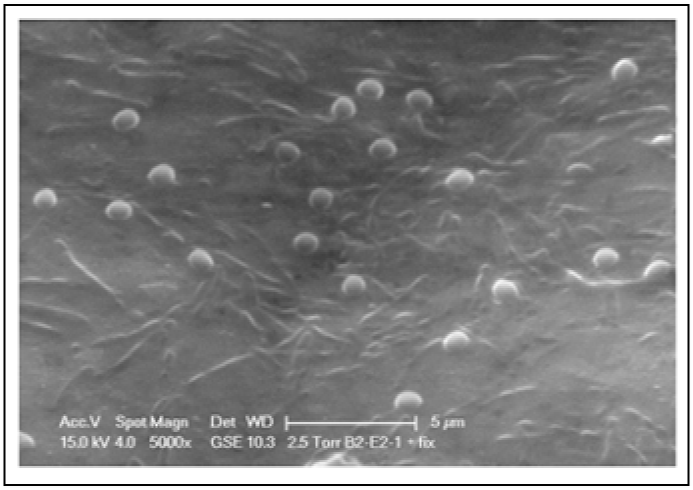

Figure 1. Alkali-resistant spore forming bacteria of the genus Bacillus. Visible are active vegetative bacteria (rods) and spores (spheres). ESEM microphotograph (5000x magnification, scale bar 5µm)

The applied self-healing agent consists in fact of two components: one is the bacteria, which thus mainly act as catalyst in a biochemical reaction, and the second is the mineral precursor component, usually calcium lactate, which is converted by the bacteria to calcium carbonate based minerals:

$$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$$

Both bacterial spores and 'feed' are stored in reservoir capsules such as expanded clay particles prior to addition to the concrete mixture (see figure 2).

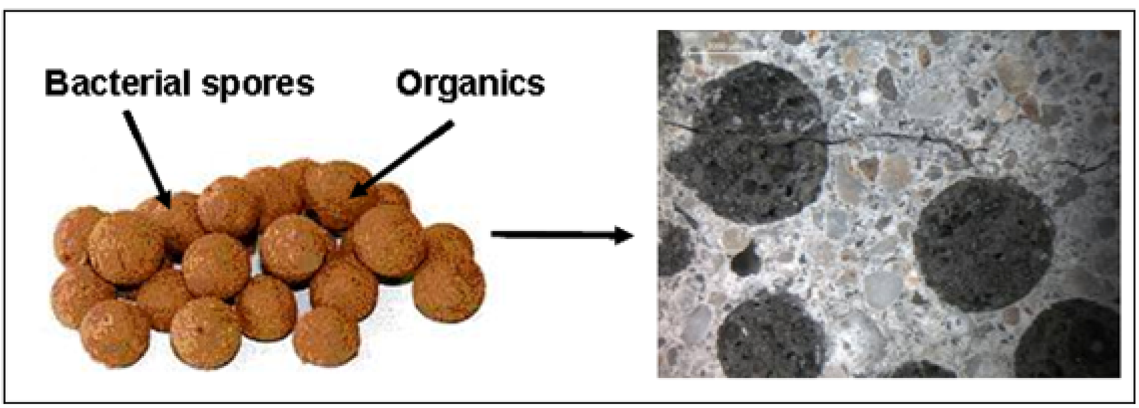

Figure 2. Self healing admixture composed of expanded clay particles (left) loaded with bacterial spores and organic bio-mineral precursor compound (calcium lactate). When embedded in the concrete matrix (right) the loaded expanded clay particles represent internal reservoirs containing the two-component healing agent consisting of bacterial spores and a suitable bio-mineral precursor compound.

In the study of Jonkers [22] concrete test specimens were prepared in which part of the aggregate material, i.e. the 2-4 mm size class, was replaced by similarly sized expanded clay particles loaded with the bio-chemical self-healing agent (bacterial spores $1.7x10^5$ g^{-1} expanded clay particles, corresponding to $5x10^7$ spores dm^{-3} concrete, plus 5% w/w fraction calcium lactate, corresponding to 15g dm^{-3}

concrete). Before application, loaded expanded clay particles were oven-dried until no further weight loss was observed (one week at 40ºC). Control specimens had a similar aggregate composition but these expanded clay particles were not loaded with the bio-chemical agent. To allow permeability testing, in both control- and healing agent containing concrete slabs a 0.15 mm wide crack was induced using a computer controlled Instron tension-compression machine (see Figure 3 for concrete slab-splitting procedure).

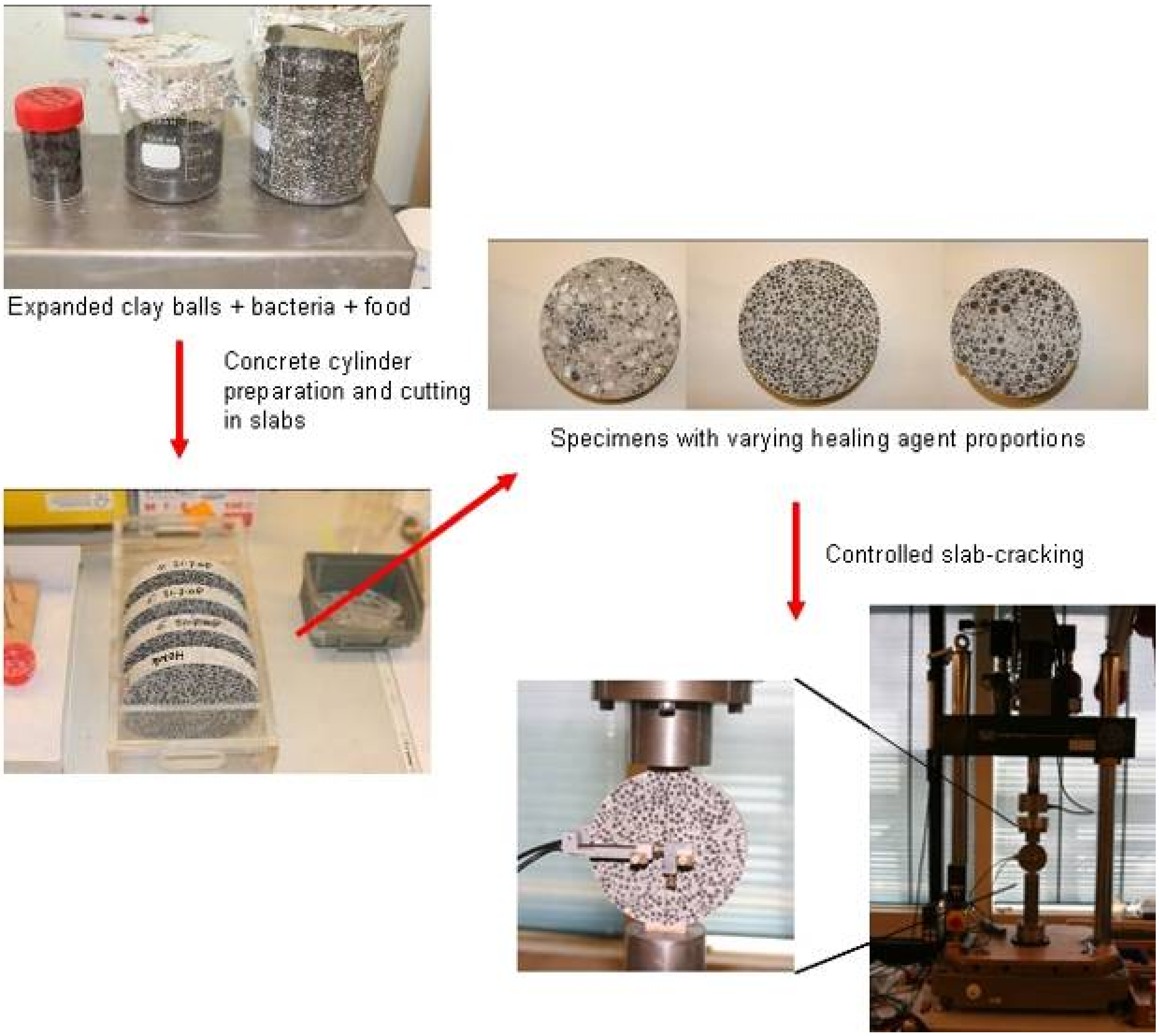

Figure 3. Concrete-cracking procedure. Concrete cylinders are cast and after 56 days setting cut in 2-cm thick slabs. Slabs are mounted in an Instron tension-compression machine, and using a fixed strain gauge in the centre of the slab, cracks are induced applying computer-controlled loading.

Six replicates of each series (control and bio-chemical agent containing specimens) were subsequently immersed for 4 weeks in tap water at room temperature to allow calcium carbonate formation to occur. Specimens were subsequently mounted in a custom made permeability testing device (Figure 4) and water permeability was quantified by determining amount of water percolating in time through the slab specimen at increased water pressure (10 cm water column plus additional 0.5 bar air pressure).

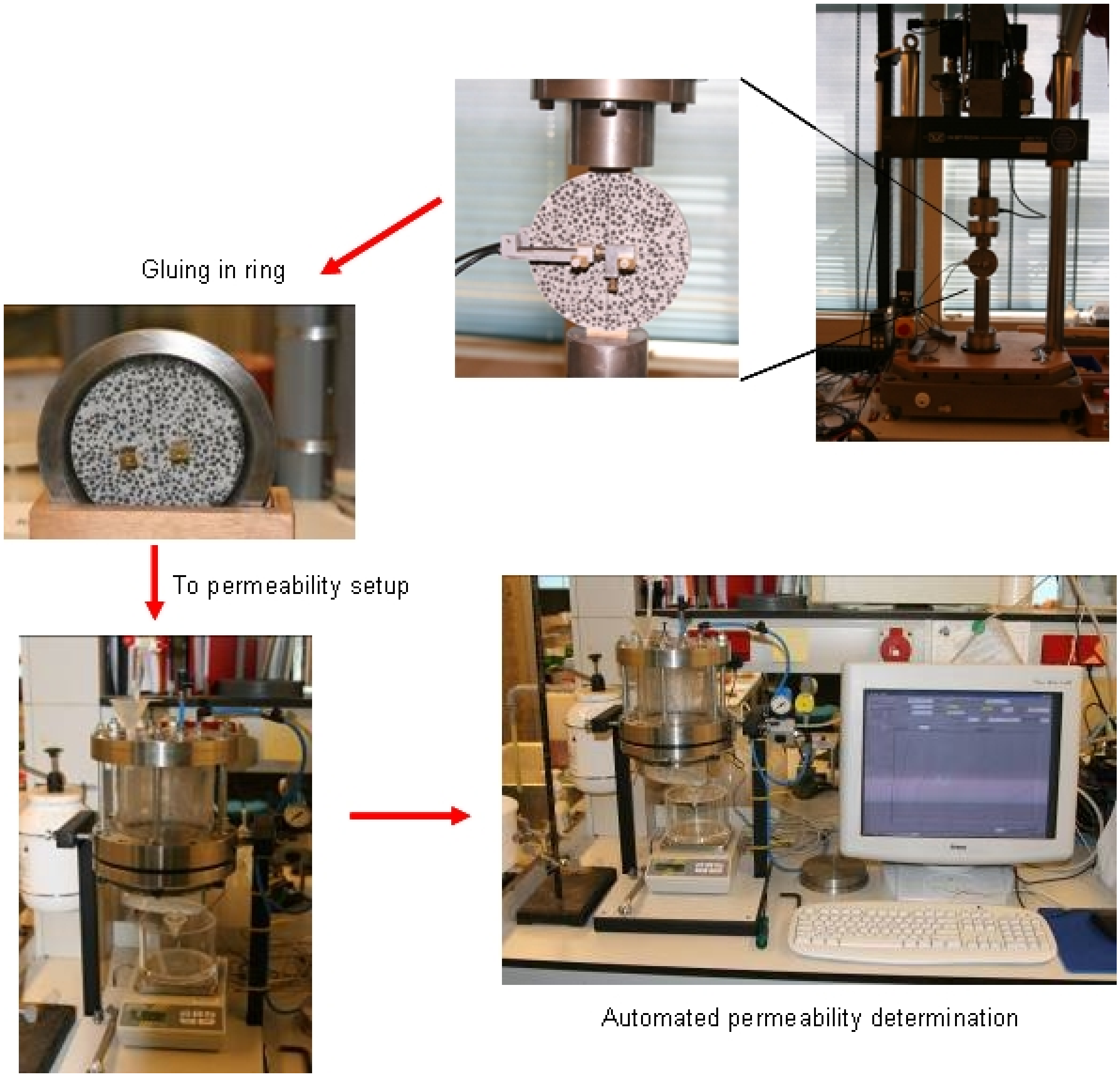

Figure 4. Concrete-cracking procedure (continued). Cracked specimen are glued in a steel ring and fitted in a custom made permeability device. The container above the mounted specimen is filled with a 10-cm column of tap water. Permeability of (healed) specimen is quantified by computer controlled measuring of percolated water in time.

Comparison between bacterial and control specimens revealed a significant difference in permeability and thus in self-healing capacity (Figure 5). While cracks of bacterial specimens were completely sealed only partial sealing of cracks in control specimens occurred. Microscopic examination of cracks showed that in both control and bacterial specimens precipitation of calcium carbonate-based mineral precipitates occurred. However, while in control specimens precipitation largely occurred near the crack rim leaving major parts of the crack unhealed, efficient and complete healing of cracks occurred in bacterial specimen as here mineral precipitation occurred predominantly within the crack itself (Figure 6).

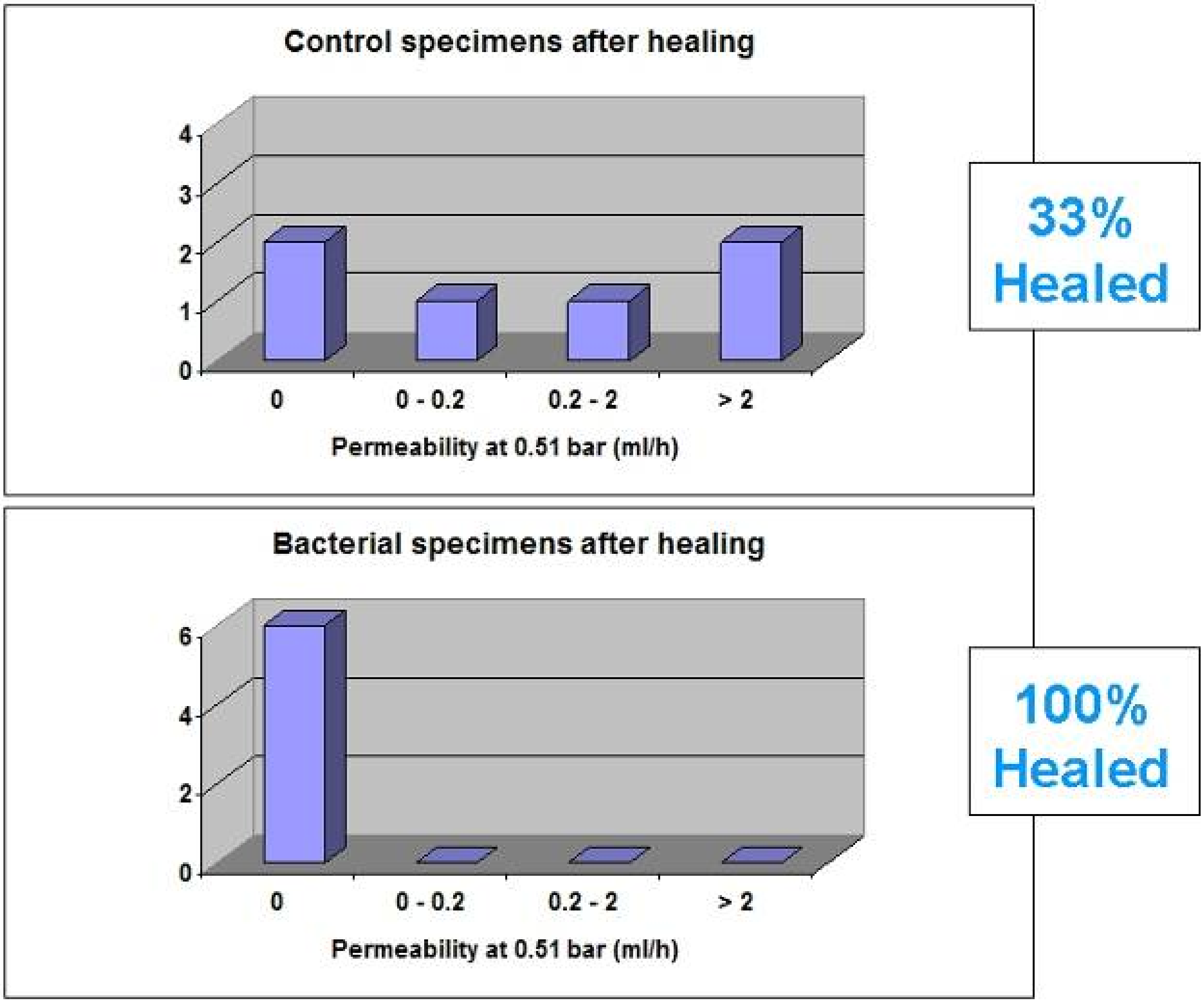

Figure 5. Permeability of cracked specimens after 4 weeks immersion in tap water at room temperature. Two out of six control specimens (top figure) and all six bacterial healing agent containing specimens (bottom figure) appeared completely sealed (at additional 0.51 bar water pressure).

The conclusion of this work was that the used two component bio-chemical healing agent, consisting of bacterial spores and feed and stored in expanded clay particles, is a promising bio-based and thus sustainable alternative to strictly chemical or cement-based healing agents. Particularly in cases where parts of a concrete construction are not accessible for manual inspection or repair could this system be a solution for increasing durability aspects.

DISCUSSION AND CONCLUSIONS

The bacteria-based concrete which is currently being developed and tested in our laboratory shows self-healing behavior. Crack-healing of concrete by bacteria-mediated calcium carbonate mineral precipitation resulted in sealing and thus water tightening of cracks. In a recent publication by Wiktor et al. [23] it was shown that in bacteria-based self-healing concrete cracks with a width of up to 0.5 mm could be healed, while healing in control specimens was limited to only 0.2 mm wide cracks.

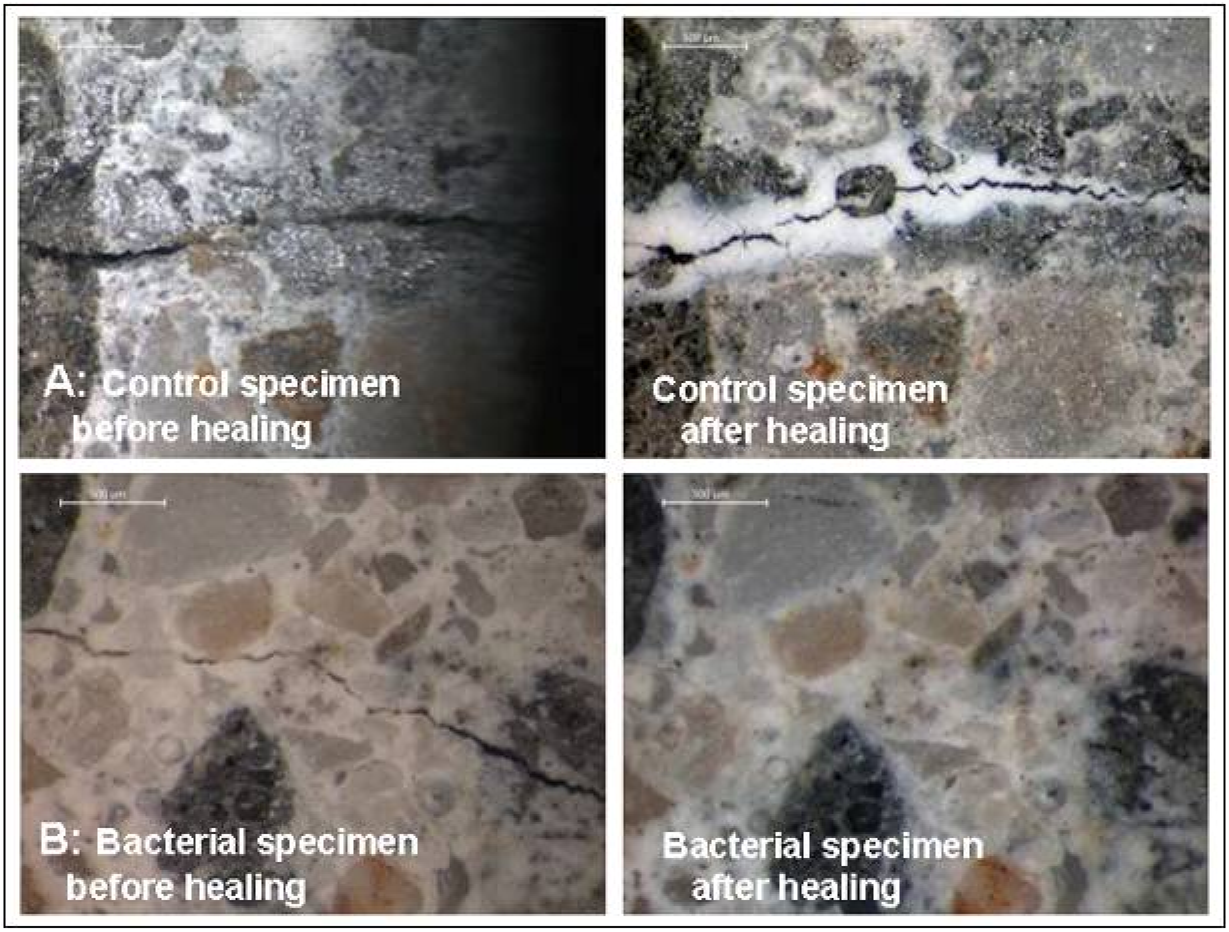

Figure 6. Stereo microscopic images (40 times magnification) of pre-cracked control (A) and bacterial (B) concrete specimen before (left) and after (right) healing by submersion in water for a two-weeks period. Mineral precipitation occurred predominantly near the crack rim in control but inside the crack in bacterial specimens.

Although the regain in strength of healed specimens still needs to be resolved it can be concluded that crack-sealing could be highly beneficial as it blocks cracks thereby reducing matrix permeability what protects the embedded reinforcement from corrosion enhancing aggressive chemical agents. This type of healing could therefore not only reduce leakage problems but also increase durability and related service life of constructions. We are convinced that this and also other recently developed self-healing materials will find their way to practical outdoors applications as certainly on the longer term these more durable materials will appear more economical in use than traditional materials.

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