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The use of alkaliphilic bacteria-based repair solution for porous network concrete healing mechanism

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Abstract

Bacteria induced calcium carbonate precipitation based on metabolic conversion of nutrients has been acknowledged for having potentials in self-healing cement-based materials. Recent studies have shown the development of bacteria-based repair solution (liquid) for concrete surface repair. This article demonstrates the feasible application of the solution as healing agent to be injected into porous network concrete (PNC). This type of concrete has a porous core which can be used as a media to transport healing agents into the fracture zone. The repair capacity of the solution have been assessed by monitoring the bio-mineral precipitation in the porous cylinder cores. The X-ray tomography and permeability tests at certain time interval were carried out before and after injection of the solution. Polished sections were prepared and examined under ESEM after healing period to investigate healing capacity. The healing potential was then tested by injecting the solution into PNC. The injection of tap water and bacteria based solution was performed through porous network until it reached and flew out through the crack which was formed by three-point bending loading. The healing efficiency was measured by water permeability test before and after injection at several time intervals. The specimens injected with bacteria based solution and cured in wet condition showed higher healing efficiency compared to dry cured specimens.

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1. Introduction

For many people not well trained in biology, the word ‘bacteria’ means something not so friendly to human. They associate bacteria with *pathogen* – agent that cause disease and infection. Though there are several deadly bacteria, the great number of bacterial communities have no connection with human. Recent studies show that bacterial ecosystem inhabits in healthy human skin, mouth, genital areas and intestine. This human microbiome – *a complex mutualism symbiotic of host-microbe* – is essential in maintaining human basic physiological processes.

Apart from aforementioned unique intricate human-bacteria relation, countless bacterial communities have direct positive effects in human life. These bacteria help human in digestion, food fermentation, and soil fertility maintenance, to name a few.

Specific to concrete technology, the potential benefit of bacteria has been investigated. Bacteria have been utilized in improving mortar strength, cleaning weathered concrete surface, restoring deteriorated limestone, and healing / sealing concrete cracks. Bacteria based concrete healing/sealing have been carried out through carbonate precipitation.

In nature, bio-mineralization (microbiologically induced calcium carbonate precipitation, MICP) precipitates calcium carbonate in three different polymorphs, calcite, aragonite, and vaterite, where calcite is the most thermodynamically stable mineral. This CaCO_3 precipitation is mediated by bacteria via different pathways – e.g. urea hydrolysis, metabolic conversion of salt and carbon, denitrification. Currently in the lab scale, several research of bacterially mediated self-healing concrete have successfully develop techniques that make use alkaliphilic calcite precipitating bacteria [1-3].

As research project spin-off, the bacteria-based repair system has been developed recently by Wiktor and Jonkers at Microlab TU Delft [4]. This bio-based system was designed in particular for repairing cracks in existing (aged) concrete. This is a liquid system comprises of three components: (a) alkaliphilic calcite precipitating bacteria, (b) nutrients and (c) transport solution. The solution is sprayed on to a concrete surface and seals the cracks leading to porosity reduction of concrete matrix.

For designing new durable building component, this contribution investigates the feasibility of the solution to block crack opening by injecting the solutions via porous core in Porous Network Concrete (PNC). PNC which was designed by imitating concrete mammalian bone morphology has pervious (porous/enhanced porosity) concrete embedded in the interior of concrete main body [5]. This air void network system constitutes an alternate means for channeling the healing agent to cracks in the main structure. Once crack mouth opens wider than a prescribed threshold value and detected by sensors, the solution may be injected automatically by the actuator.

2. Materials

2.1. Bacteria based repair solution

Jonkers and Schlangen [6], Jonkers et al. [7], and Wiktor and Jonkers [8] designed self-healing concrete by means of bacteria mediated calcite precipitation through metabolic conversion of nutrients. It is required that the bacteria resistant to alkaline environment as in fresh concrete matrix and have sufficient tolerances to oxygen. The bacteria should be able to form spores in order to be viable in very long time. As the encapsulated bacteria convert the nutrients when crack intersects the capsule, the microenvironment next to the bacteria cell is conducive for calcite to precipitate. With this mechanism bacteria help sealing crack for newly designed concrete.

On the other hand, existing aged concrete shows distress and crack due to mechanical or environmental load. This damaged concrete was not designed in first place to have self-healing capability. They demand repair using ecologically friendly repair material. This situation motivated Wiktor and Jonkers to design a bacteria-based repair system with easy and quick application [4]. The solution is applied by spraying the solution onto the surface of a cracked concrete structure, where it yields to crack closure.

For this investigation the solutions were prepared based on Wiktor and Jonkers [8]. The bacteria-based repair system consists of two types of solutions namely A which is composed of bacteria, nutrients and pH buffer compound and B containing a calcium source to promote massive calcium carbonate precipitation.

2.2. Porous core and Porous Network Concrete

One important aspect to make concrete self-healing is the transport of healing agent into the damage i.e. fracture or crack zone. In organisms, nutrients transport appear at micro level by means of cellular transport and via vascular system in the macro level. In concrete transport of substance is influenced by several factors; such as gradients of temperature, pressure, humidity, or solution concentration. Without external driving force, these intrinsic factors, however, might not enough to transfer healing agent to the fracture zone.

Imitating bone shape, Porous Network Concrete was designed by Sangadji and Schlangen [5], by embedding this porous concrete core as interior of conventional concrete. PNC consist of two type of concrete; normal (dense) concrete and pervious concrete as porous core. Both concretes are made of cement, water, and aggregate where some admixtures may be added to achieve specified criteria. In pervious concrete, fine aggregate is not used and narrow distribution of coarse aggregate is employed. The porous core which has interconnected void, thus liquid to certain level of viscosity can flow easily, is used as a channel for healing agent.

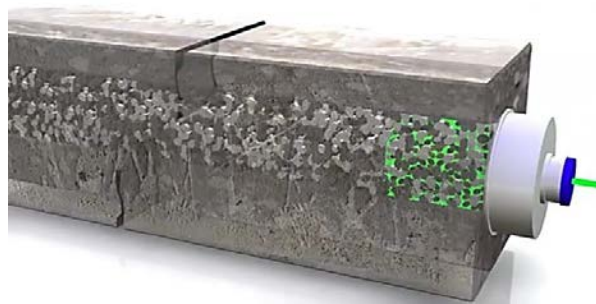


Fig. 1. Conceptual working principle of healing agent transport in the Porous Network Concrete.

Fig. 1 shows a semi-transparent picture depicting PNC with porous concrete core inside of dense concrete beam. The system shows healing agent start flowing through the porous core which eventually will reach the crack and sealing it inside out.

In this research program, PNC was prepared as described by Sangadji and Schlangen [9] as concrete prisms with dimension of $55 \times 55 \times 285$ mm PNC specimen. Each specimen center interior is $23 \times 23 \times 285$ mm porous concrete and $\varnothing 2$ mm threaded steel rebar was installed under the core. Bacteria based solution was injected from point of injection.

3. Research methods

3.1. Calcite precipitation in the porous core

It is predicted that the bacteria-based repair solution can seal the crack in the concrete after it is injected via porous network core. To determine whether the hypotheses work well, it is necessary to investigate biomineralization process takes place in the concrete core when the solution is injected. Porous concrete cores with diameter of 2.5 cm and height of 3 cm of were cut form longer core which was prepared according to Sangadji et al [9].

Five series (A,B, C, D and Control) of test were designed to assess repair capacity of the solution in porous concrete core. Two replicates were used per time and series where test have been conducted 3, 7, 14, 21 and 28 days after injection except for series D (only 28 days is tested). Porous core in series A were treated with 1 time injection and sequence: sol A and then sol B. Series B were treated with 1 time injection with static mixing nozzle by which solution A and B were mixed. Series B were treated with 3 times injection and injection sequence as series 'A'. Series D were treated as series 'A' but only food solution is injected without bacteria. And lastly, Control series were injected with tap water only.

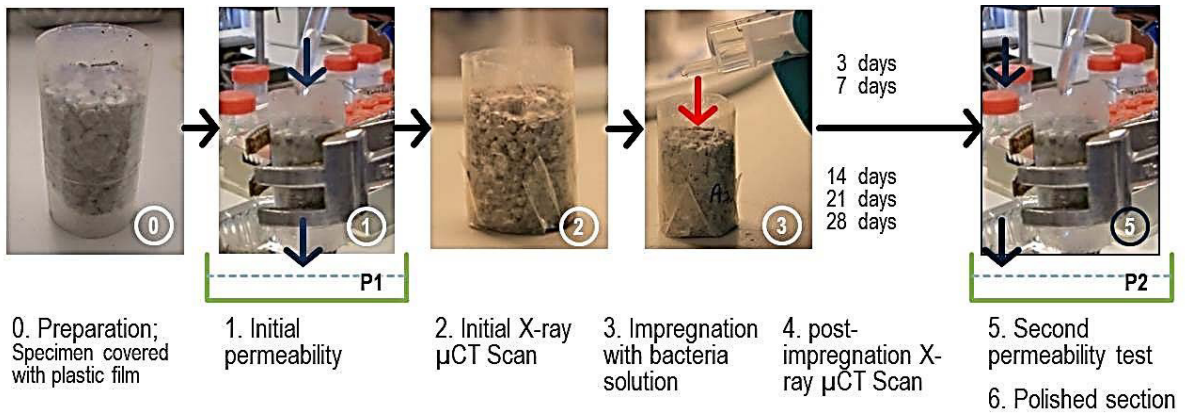


Fig. 2. Sequence of the test.

To assess the repair capacity of the system the bacteria-based solution is injected into porous cores, and the production of bio-minerals in time is monitored by X-ray micro-tomography. In parallel, water permeability test is conducted before and after the injection of the bacteria-based solution at regular time interval to determine the sealing efficiency of the system. Finally, at the end of the healing period, polished sections of injected specimens are observed with ESEM/EDS to analyze and locate bio-minerals. The sequence of the test form material preparation, injection and permeability test is shown in Fig. 2.

3.2. Crack sealing in the main body

A research program has been devised to implement injection of bacteria based solution into Porous Network Concrete (PNC) prism. Two type of treatments were implemented with 2 replicates. The ‘control’ series received injection of tap water and ‘bacteria’ series received injection of bacteria-based solution. Two different curing were conducted in which ‘wet’ series were cured in $\pm 95\%$ RH and $\pm 20^\circ\text{C}$ curing chamber while ‘dry’ series were cured under lab condition with RH $\pm 30\%$ and temperature $\pm 20^\circ\text{C}$.

Initial permeability test was performed by flowing water from point of injection (a) to the opposite point outflow (b) prior to crack formation, as depicted in Fig. 3.a. Then, crack formation in the prism mid-span was carried out by means of strain controlled three point bending, as depicted in Fig. 3.b. Initial crack width in the beam bottom side was achieved around $\pm 250 \mu\text{m}$. The pre-healing permeability test, the, was performed by blocking point (b), therefore water leaked out from crack opening. After the core achieved saturated surface dry, then PNC prism was injected with 30 ml of water for ‘control’ series and ‘bacteria’ series specimens were injected with solution A and B into. Afterwards, specimen were cured under lab condition and in the humid fog room prior to after-healing permeability test and second mechanical three point loading.

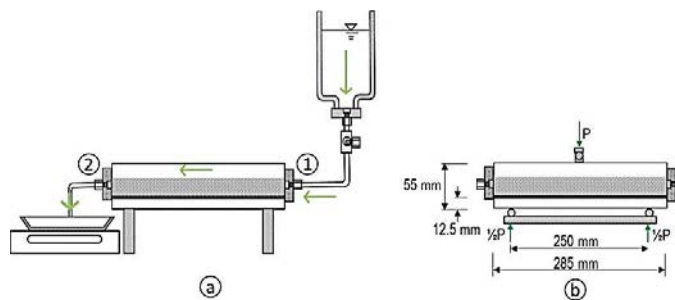


Fig. 3. a. Falling head permeability test, b. strain controlled three-point bending

Crack closure has been monitored before and 7, 14, 21, and 28 days after injection under stereomicroscope. Quantification of crack-healing has been carried out using the method as described by Wiktor and Jonkers [8]. 28 days post-healing permeability test was executed to measure permeability reduction.

4. Result

4.1. Repair capacity of bacteria-based solution in the porous core

There is a diverse data observed from water permeability test in porous concrete before and after bacteria-based solution injection with setup as depicted in panel 1 Fig. 2. The reason is that the specimens are very porous with average void diameter of 1 – 1,5 mm and the volume CaCO_3 precipitation is not enough to block the total void. In line with the observation above, data processed from micro CT-scan reveal similar outcome. Three day after injection, approximately 6% new material is found in the porous core which decreased to 2% after 7 days and remain constant up to 28 days. The bacteria injected may not produce high amount of CaCO_3 precipitation and after 3 days only solution is detected with the CT-scan. Further the solution dries out over time and the volume detected decrease leading to difficulty to distinguish between organic precipitates (from nutrients) and bio-minerals. It can be deduced that both techniques, permeability and CT-scan, provide no meaningful indicator of bacteria-based solution's repair capacity within porous core.

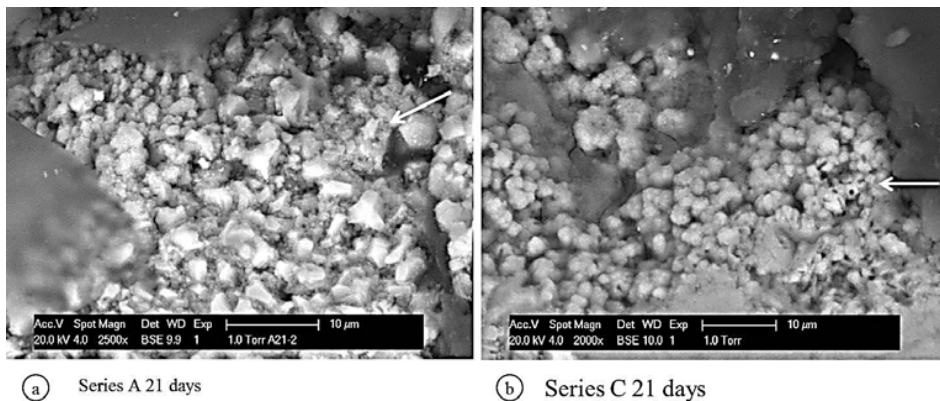


Fig. 4. a. Ca-based crystal formation within the specimen Series A at 21 days after injection, b. CaCO_3 formation in the porous core where bacteria imprints indicate that it entombed after crystal formation grows in the vicinity of the bacteria.

Observing porous core polished section under ESEM, however, it was found several cavity between epoxy and the porous core matrix in series containing nutrients, but not in 'control' series injected with tap water only. The reason was the nutrients entrapped dissolved when the polished specimens were ground on top of sand paper for 45 minutes with water. Yet, this 'bad bonding' is a good sign to locate the existence of nutrients and bio-minerals converted from it by bacteria.

Calcium based crystal are observed to be exist in the series A at 21 days after injection even though in small volume. The crystal is shown in the Fig. 4.a. More Ca-based crystals are detected in specimens of 28 days after injection which may be induced by bacteria. Similar indication is observed in series B though it seems that the amount of crystal formation is smaller than series A.

Larger number of cavity in between epoxy and concrete matrix is observed in series C. This is coherent with the case that more nutrients and bacteria are injected into the porous core series C by factor of 3 compared to series A. Furthermore, it is found a strong indication of bacterial activity in the concrete matrix in the form of bacteria imprint, as depicted in Fig. 4.b, for specimens of 21 and 28 days after injection. Found in several location this imprints indicated bacteria are active and consume the nutrients to cultivate and reproduce. While bacteria growing, the chemistry in the area next to its cell wall changed and with the present of Ca ions the supersaturation condition is

achieved leading to the formation of CaCO_3 . As nutrients dissolved in the series D, many cavities are observed in the specimens but no bacteria mediated calcite precipitation is observed.

It is deduced from the experiment that there is potential of healing capacity by means of CaCO_3 formation where alkaliphilic bacteria are an indispensable element of the system. Nevertheless more external Ca-salt is needed in the system to produce more CaCO_3 formation amount necessary to seal crack formation.

4.2. Self-healing capacity in PNC prism

For PNC prisms the results of initial permeability showed that porous core is pervious and after crack formation in the mid-span there was water leakage from the crack opening. Fig. 5.a. and 5.c. show the crack path in the bottom of the PNC specimen after three-point bending test. From this crack formation liquid can flow out or in to the concrete matrix.

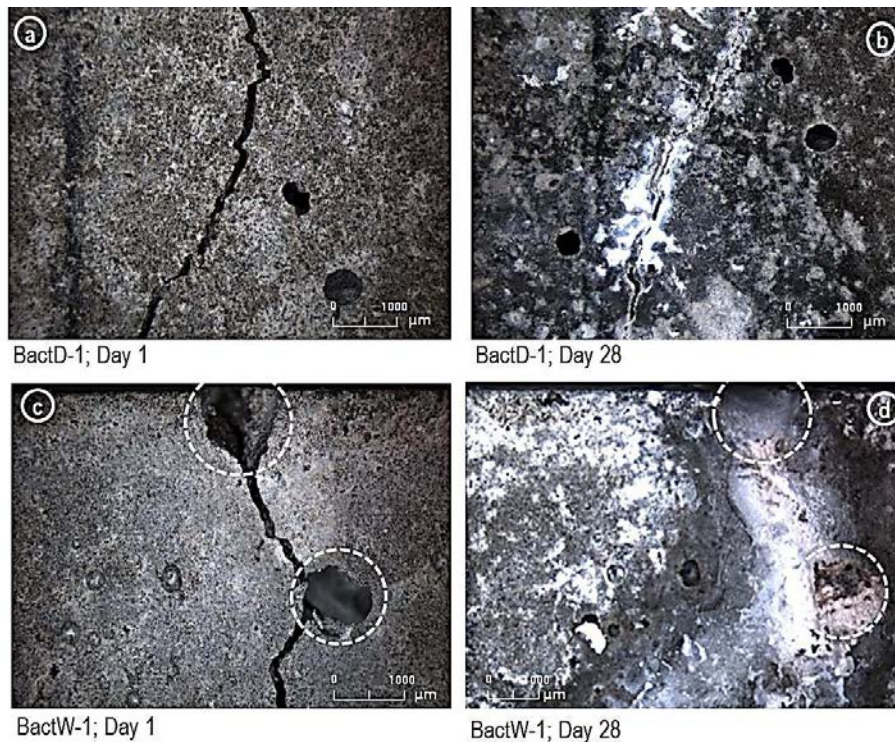


Fig. 5. a. Crack of in the PNC prism after three point bending test (1 day), b. CaCO_3 formation in the crack of dry cured PNC, c. Crack of in the PNC prism after three point bending test (1 day), d. precipitation of bio-minerals in the crack zone for wet cured PNC.

The experiment showed that wet cured bacteria series exhibited complete permeability reduction as it can be seen from the Fig. 5.d., where precipitation of bio-minerals blocks the crack path therefore no water cannot flow out from permeability test. Meanwhile dry cured specimen shows limited reduction as seen in Fig. 5.b. It can be deduced from the experiment and visual observation under microscope that the liquid tightness of the healed specimen is obtain fully using bacteria based solution injected provided enough humidity for the bio-mineralization process.

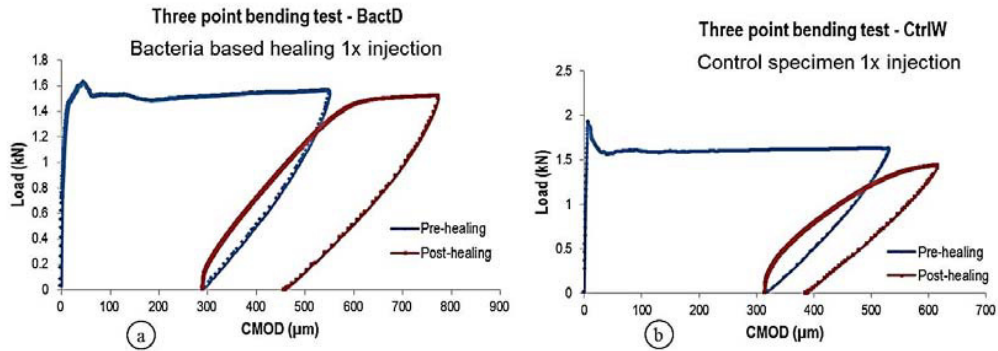


Fig. 6. a. Load-crack mouth opening displacement (CMOF) graphs of bacteria based healing specimen, b. Loading cycle graphs of control specimen.

Load versus Crack Mouth Opening Displacement (CMOD) is obtained from three-point bending test. This mechanical test is used to indicate the strength of PNC in pre- and post-healing state. Fig. 6 show the result of PNC with bacteria based healing system (a) and control specimen which only receive tap water injection after crack formation. Second cycle three-point loading was carried out to assess whether the bio minerals precipitated in the crack zone contribute to regain the strength as it is compared to pre-healing loading cycle. The curves of loading cycle obviously show limited strength and stiffness regain in both bacteria based or control specimen. The peak load of post-healing specimen is lower than the peak load of the virgin specimen. The post-healing stiffness of both systems are also far less than the pre-healing. It was observed that the crack formation was just reopened due to the second loading cycle and the post-healing strength and stiffness more less was provided only by the rebar embed in the PNC.

5. Conclusions

The bacteria based repair solution, firstly designed for concrete surface crack repair, showed promising potential as healing agent which can be injected via porous network. The precipitation of bio-minerals, mainly CaCO_3 , can seal the crack formed in the PNC main body, where multiple injection appear to be the most efficient way to obtain sufficient volume of the bio-minerals. The bio-mineralization indeed is induced by alkaliphilic bacteria as bacterial activity in the form of bacteria imprint is found in the system. Even though mechanical regain in term of strength and stiffness of bacteria-based post-healing PNC prism is quite limited, crack sealing works effectively and liquid tightness may be assured.

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