Application of bacteria-based repair system to damaged concrete structures

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ABSTRACT: The goal of this study is to present the development of bacteria-based repair system which features improved durability and sustainability characteristics compared to currently commercially available systems. This paper presents the results on the development of bacteria-based systems to be applied in different situations: (i) relatively new concrete and/or in presence of oxygen, and (ii) highly carbonated concrete and/or moderate concentration of oxygen. The results showed that the system composed of alkaliphilic bacteria (for new concrete) can successfully be applied (in 2 steps) on concrete structures as it results in complete closure of the cracks. Furthermore, this system is being tested on large scale. Then, the authors presented a second bacteria-based system. The first results are very promising as denitrifying bacteria can successfully mediate mineral precipitation. This system is of great interest for the repair of underground concrete structures where oxygen can be limited.

1 INTRODUCTION
Concrete is strong and relatively cheap, but it is also subjected to a number of degradation processes which hamper the structure to reach its required service life. To anticipate durability problems during the lifetime of a structure, costly measures of maintenance and repair have to be undertaken.

Currently available concrete curing and repair system aiming to decrease porosity and repair of cracks in aged concrete structures are largely based on environmental unfriendly materials systems. Moreover, periodic maintenance operations for concrete structures are generally focused on repairing concrete damages while not considering the relevant durability issues of the repair system itself (Robery, 2011; Tilly and Jacobs, 2007). Premature failure of repairs and lack of certainty in the durability and performance of some repaired structures affects Europe and many part of the world. Accordingly, there is a need to achieve more durable repaired concrete structures (Matthews et al., 2007).

With respect to these considerations, the present study focuses on the development of a bio-based repair system. The basic idea is considered a spin-off of the recently developed bio-based self-healing concrete where cracks are filled with calcite produced by incorporated bacteria (Jonkers, 2011; Wiktor and Jonkers, 2010). The main goal is to develop a bio-based repair system which features improved durability and sustainability characteristics compared to currently commercially available systems.

This paper is divided in two parts and gives an overview on the bio-based repair systems developed in Delft University of Technology. First, the authors introduce the requirements and working principle of bacteria-based repair system. Then, in the second part, the authors present the results on the development of bacteria-based systems to be applied in different situations: (i) relatively new concrete and/or in presence of oxygen, and (ii) highly carbonated concrete and/or moderate concentration of oxygen.

2 BACTERIA-BASED REPAIR SYSTEM: WORKING PRINCIPLE
The bio-based repair system developed in this study is a liquid-based system which transports a bio-based agent into concrete. The bio-based repair agent consists of bacteria and feed which produce calcite-based minerals decreasing concrete matrix porosity.

The bio-based system is composed of three compartments (Fig. 1): Transport solution, bacteria, and nutrients. Each compartment should be wisely chosen in order to keep properties of the two others optimum.

2.1 Transport solution
The transport solution ensures the transport of bacteria and nutrients into the concrete via the cracks or
porosity. The pH of the transport solution should promote bacteria development, and prevent premature precipitation of nutrients.

![Diagram of Bacteria and Nutrients](image)

**Figure 1: Liquid-based system developed in this study.**

2.2 Bacteria

Bacteria can metabolically convert dissolved precursor compounds (nutrients) into calcite-based minerals.

2.3 Nutrients

To produce calcite-based minerals bacteria need organic carbon and calcium source. The nutrient source should be chosen in order to promote optimum bacterial activity.

2.4 Selection of two promising systems

Recently, bacterially mediated calcite precipitation thanks to metabolic conversion of calcium lactate has been successfully applied in self-healing concrete (Jonkers, 2011; Wiktor and Jonkers, 2010; Wiktor and Jonkers, 2011). The bacteria used are alkaliphilic species from the genus *Bacillus* which grow in alkaline environment such as in concrete.

However, the alkali-resistant bacteria will develop under high pH (>9) and in presence of oxygen. Hence, in the case of highly carbonated concrete structures and/or moderate concentration in oxygen like for underground structures, the efficiency of this bio-based repair system can be limited.

Therefore, denitrifying bacteria are also considered in this study as an alternative for the repair of aged carbonated concrete structures using bio-based system. The denitrification is the biological reduction of nitrogenous oxides to gaseous products during anaerobic (no oxygen) bacterial growth. This means that under the metabolic conversion of suitable nutrient, N\(_2\) and calcium carbonate are produced. Moreover, during this process the pH of the solution increases.

3 DEVELOPMENT OF BIO-BASED REPAIR SYSTEMS

3.1 System with alkaliphilic bacteria (new concrete)

3.1.1 Materials and methods

Mortar discs (\(\varnothing 17\text{cm} \times \text{h}=2\text{cm}\)) were cast with ordinary Portland cement and aggregates (0-4mm) in plastic buckets. The specimens were kept 28 days in sealed conditions at room temperature and then tested for 3 points bending test until failure. The bottom of the buckets is removed and the cracked mortar discs were glued in the buckets (Fig. 2).

Permeability test is performed before and 28 days after impregnation with the bacteria-based repair solution: the amount of water permeating through the crack in 1 hour is recorded. The permeability value before repair is noted \(P_1\) and the one after \(P_2\). The difference between these 2 values gives an estimation of the efficiency of the crack repair.

Based on previous works from Wiktor and Jonkers (Wiktor and Jonkers, 2012a; Wiktor and Jonkers, 2012b; Wiktor et al., 2012), a system composed of alkaliphilic bacteria and sodium gluconate (nutrients) in a sodium silicates solution (transport solution) was selected as it promotes the bacterial growth, mineral formation and densification of the microstructure. This solution is called solution A.

However, in order to promote massive calcium carbonate formation for crack repair, an impregnation of concrete specimens in two steps is also considered in the present paper. Hence, one step impregnation is impregnation of the mortar specimen with solution A only, and two steps impregnation is impregnation with solution A and a second solution containing a calcium source (solution B).

Control specimens are impregnated with tap water only.

3.1.2 Results

The results are presented in figure 3. First, impregnation with bacteria-based repair solution shows higher permeability decrease compared to control solution. This can be attributed to the bacterially-mediated mineral precipitation inside the crack. It can also be observed on figure 3 that 2 steps impregnation appears very promising as it leads to almost complete closure of the crack. This could be explained by the massive calcium carbonate formation thanks to the calcium source in solution B.

However, it can also be noticed that the permeability of the control specimens is higher after impregnation with tap water. This could be due the loss of material during the permeability test which can not be replaced by mineral formation in that case.
a. Casting of mortar discs  

\[
\text{bucket} \\
\text{Ø}=17\ cm \cdot h=14\ cm
\]

b. Breaking of specimen  

c. The bottom of the bucket is removed  

d. Specimens are glued inside the buckets

Figure 2: Preparation of mortar specimens

![Diagram of mortar discs and buckets]

3.2 System with denitrifying bacteria

The goal of this experiment is to determine which is the best combination "bacteria-nutrient-transport solution" to be used on carbonated concrete or when the concentration in oxygen is limited.

3.2.1 Materials and methods

Three prismatic mortar test specimens (4x4x16cm) were cast with OPC and aggregates size 0-2mm, and kept 28 days at room temperature under plastic foil. They were then sawed in small cubes of 1cm³. Only cubes which were cut on all sides were used for the experiment.

The cubes were exposed to accelerated carbonation (50%RH – 5% CO₂) for 2 weeks and then immersed 1h in a repair solution. The repair solution varies in terms of concentration of nutrients.

After 7 and 28 days in water saturated atmosphere, the cubes were directly monitored with ESEM/EDAX to study the influence of the treatment on the sample surface and to observe the morphology of the newly formed minerals.

3.2.2 Results

The specimens immersed in a solution with low concentration of nutrients showed mineral formation after 7 days comparable to the control (immersed in tap water) (Fig. 4a), which suggests that the surface layer formed is probably calcium carbonate formed by carbonation of the matrix. On the other hand, the specimens exposed to higher concentration in nutrients exhibits crystals after 7 days significantly larger than that of the control specimens (Fig 4b). Moreover the deformed rhombohedra shape suggests that the mineral may be CaCO₃ and its formation could be the result of the metabolic conversion of the food by bacteria.

This is confirmed by the observation of bacteria imprints at the surface of the mineral after 28 days (Fig. 4c,d).

These preliminary results enabled us to determine the minimum concentration in nutrient required to promote significant bacterial growth and therefore mineral precipitation.

More investigations are needed to estimate the repair potential of this system in anoxic conditions.

4 CONCLUSION

The aim of this paper was to present the potential of bacteria-based systems for the repair of damaged concrete structures.

First, the authors presented a liquid repair system composed of alkaliphilic bacteria which can be applied to relatively new concrete structures, and when oxygen is not limited. The results showed that this system can successfully be applied (in 2 steps) on concrete structures as it results in complete closure of the cracks. This system is currently being tested on large scale on a real structure; the results are expected in the near future.

Then, the authors presented a second bacteria-based system, which could be applied on highly carbonated concrete and when the concentration in oxygen is limited. The first results appear to be very promising as denitrifying bacteria can successfully
mediate mineral precipitation. Further analyses are needed to identify the nature of the mineral formed and to evaluate the repair potential on cracked concrete specimens. However, this system is of great interest for the repair of underground concrete structures where oxygen can be limited.

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REFERENCES


Figure 4: ESEM observations of the surface of mortar specimens after immersion in repair solution containing denitrifying bacteria. 7 days after immersion in solution with (a) low and (b) high concentration of nutrients. (c) 28 days after immersion in solution with high concentration of nutrients, (d) zoom of picture c, the arrows shows bacteria imprints.