

## Self-Healing of Cracks in Concrete with Bacteria

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### Abstract

During the service life of concrete structures, internal and external effects and micro-cracks occur in the structure. These cracks cause leakage of harmful substances into the concrete, deterioration of the strength and durability properties of the concrete, structural damages and crashes, and the high cost of maintenance and repair of the concrete structure. It is known that water-dissolved CO<sub>2</sub> reacts with Ca<sup>+2</sup> ions in the concrete and can repair the concrete by forming CaCO<sub>3</sub> (limestone) crystals with very little water solubility. However, for this type of self-repair to occur, there must be water in the environment and this repair can only be made if the cracks are too small. Recently, bacterial concrete methods which has ability to self-healing are used to overcome maintenance and repair costs. In 1994, the first study on the ability to self-healing with the extra materials that were added to the concrete during the production of concrete was published by Carolyn Dry of Illinois University. Eric Schlagen and Henk Jonkers who have been researching about self-healing concrete by adding bacterial spores and calcium lactate foods to the mixture while producing concrete have made a remarkable study in this field since 2006. Bacterial concrete, Bacillus bacterial spores in the medium of the water-activated nutrients and calcium sources in the range of appropriate pH values in the concrete due to the formation of a fibrous structure is caused by precipitation of calcite. Thus, with the precipitation of calcite, the bacteria are embedded in concrete and the concrete is provided to improve itself. In previous studies, it has been shown that the cracks and voids in the concrete are filled with the ethrengite and C-S-H structure when the control and bio-based concrete samples examined by SEM and XRD are compared. In previous studies, it was

observed that mechanical strength and durability of the concrete is increased. It should be noted that the concentration of bacteria used in the solution and the ambient pH value is specified. Although conventional maintenance and repair methods are fast reacting, and short-term efficient, bacterial concrete method is sustainable, slow and long-term efficient. In addition, it is an environmentally friendly method compared to chemical repair methods and is expected to be among the remarkable materials of the future. The high initial cost leads to a reduction in producer demand, and the development process must continue to achieve the desired results and cost. As a result, it will be possible to obtain more durable structures by not wasting time, saving money and reducing the costs of high maintenance and repair. In other respects, it is a great advantage for sustainable development. Technical studies are continuing due to the high cost and laboratory test results of the bacterial family, as well as the impacts on the survival of the bacterial family. In this study, previous studies were evaluated, and some suggestions were made based on these studies.

**Keywords:** Self-healing concrete; micro-cracks; bacteria; humidification; bacillus pasteurii

## Introduction

Concrete, the most popular construction material that has been used in the world. But concrete has brittle mechanical behavior and environmental impacts effect physical and chemical structure of concrete, so this environmental impact is to cause to micro-cracks. Occurring mechanism of cracks which are inevitably in concrete due to its relatively lower tensile strength and action of different load and non-load factors may be varied including plastic shrinkage, drying shrinkage, thermal stresses, external loading and rebar corrosion or coupled effect of multiple factors (Souradeep et al. 2017). These cracks cause leakage of harmful substances into the concrete, deterioration of the strength and durability properties of the concrete, structural damages and crashes, and the high cost of maintenance and repair of the concrete structure. When growth of micro-cracks reaches from the surface of concrete to the reinforcement, corrosion occurs on reinforcement due to attack of aggressive agents (water, oxygen, CO<sub>2</sub>, chlorides, etc.) which corrodes the reinforcement reducing its service life. The rate of aggressive agents' ingress into concrete is primarily dependent on the internal pore structure of concrete (Vijay et al. 2017). Therefore, it is more important to prevent these cracks at the start or it will become a major crack, however, to repair this crack is not an easy task so some alteration is needed in the construction material (Kulthe et al. 2018).

In 1994, C. Dry was the first who proposed the intentional introduction of self-healing properties in concrete (Van Tittelboom and De Belie 2013). In recent years, there are many alternative repair mechanisms and one of them is based on the application of biomineralization of bacteria in concrete. Biomineralization is a biochemical process in

which microorganisms stimulate the formation of minerals (Bundur et al. 2017). Bacteria induced mineral precipitation has been suggested by researchers as an alternative and environmental technique for crack repairing and sealing. The objective of this study is to summarize and compare the results of some researches published previously on properties and techniques of bacteria-based concrete which vary with the addition of bacteria. First, different theoretical approaches to bacteria-based concrete were explained. Afterwards, the results of some researches published previously on properties and techniques of bacteria-based concrete were summarized and compared.

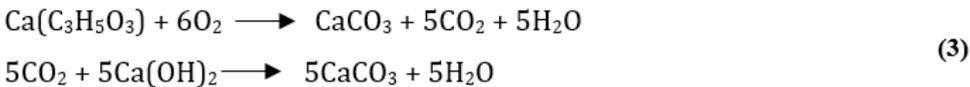
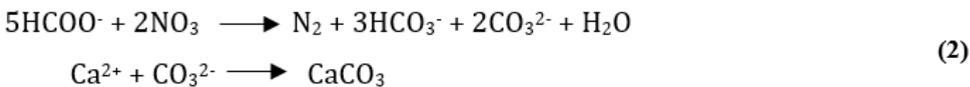
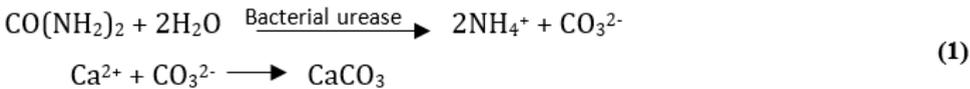
## Theory

A variety of techniques is available but traditional repair systems have several disadvantageous aspects such as different thermal expansion coefficient compared to concrete and have impact on environment and health (Rao et al. 2013). Application of traditional crack repairing systems usually contains applying a cementitious material-based mortar bonded to the damaged surface, which can be especially time consuming and expensive in concrete structures due to mostly difficult to get access to repair cracks. Biotechnology and nanotechnology are used to improve the properties of concrete. Consequently, bacteria-based concrete has been suggested as an alternative and sustainable crack repair technique. The conceptual idea provided by bacterial crack healing mechanism is that the bacteria should be able to transform soluble organic nutrients into insoluble inorganic calcite crystals which seals the cracks (Rao et al. 2013). Concrete has a rather aggressive medium due to its high internal pH, relative dryness and lack of nutrients for common bacteria needed for growth, however, some extremophilic spore forming bacteria can survive in this medium and increase the strength and durability of concrete (Rao et al. 2013). But, the bacteria will not survive once the cells become jammed by  $\text{CaCO}_3$  crystals and the bacterial activity will also come to an end once all nutrients are consumed. Therefore, it can be concluded that even the bacterial approach will not allow an endless repetition of the healing process (Van Tittelboom and De Belie 2013).

Concrete durability and permeability has a strong relationship. Bacteria-based concrete biologically produces calcium carbonate crystals to seal cracks. Calcium carbonate ( $\text{CaCO}_3$ ) that is a common substance found in rocks exists in environments such as marine water, fresh water, and soils. There are many techniques to heal properties of concrete, among these techniques' bacteria-based concrete that special strains of bacteria capable of precipitating certain chemicals are used is a relatively new technique. According to Rao et al. (2013), autogenous healing occurs because of hydration of non-reacted cement particles present in the concrete matrix once meet leakage water resulting in in closure of micro cracks, however, due to the variability of autonomous crack healing of concrete micro cracks can still occur. The bacteria used in concrete should be able to have long-term effective crack sealing mechanism during its lifetime serviceability. Recent researches about bacteria-based concrete focus to heal cracks

induced after 28-days of casting, which can be mentioned as an early age application for bacteria-based concrete (Bundur and Amiri 2016).

The mechanisms of microbially induced calcium carbonate precipitation (MICCP) can be achieved through different pathways like urea decomposition, oxidation of organic acids (aerobic process), or nitrate reduction (anaerobic process). Therefore, the effects of bacteria on concrete strength are variable. The precipitation rate of biological calcium carbonate is ideally influenced by concentration of calcium ions, pH of the solution, concentration of dissolved inorganic carbon and availability of nucleation sites. Alkali tolerant ureolytic strains, such as *Sporosarcina pasteurii* (*Bacillus pasteurii*), *Sporosarcina ureae*, *Bacillus sphaericus*, and *Bacillus megaterium*, that can decompose urea into ammonium/ammonia and carbonate ions (Equation 1) are the most commonly used bacteria in bacteria-based concrete. Bacterial urea hydrolysis requires oxygen to initiate bacterial activity (spore germination), which can be a restricting factor for deep crack healing. Nitrate reduction by different strains, such as *Diaphorobacter nitroreducens*, under oxygen limited conditions, denitrifiers use nitrate ( $\text{NO}_3^-$ ) to generate  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$  ions, which are necessary for  $\text{CaCO}_3$  precipitation (Equation 2). The alkaliphilic strains, such as *Bacillus cohnii*, *Bacillus pseudofirmus* and *Bacillus alkalinitrilicus*, which can degrade organic compounds into  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , and  $\text{CO}_2$  can be easily converted to  $\text{CO}_3^{2-}$ , and with the presence of  $\text{Ca}^{2+}$ ,  $\text{CaCO}_3$  can be formed (Equation 3).



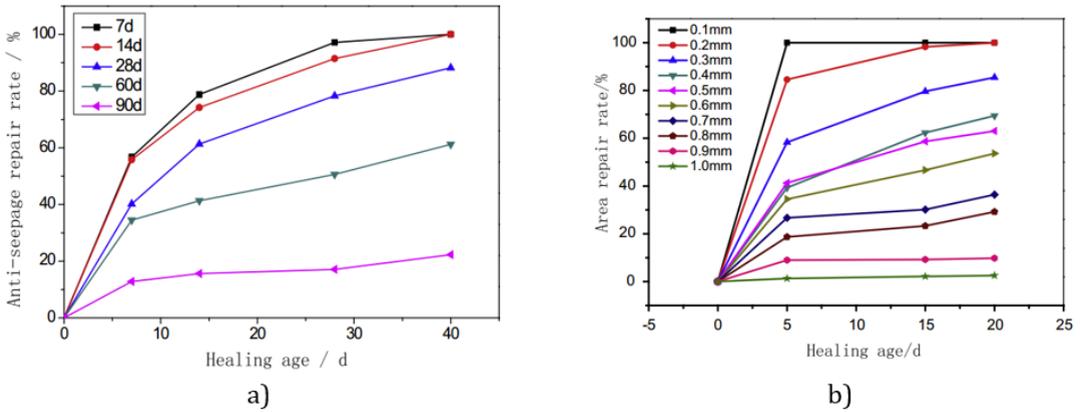
There are some basic approaches for crack healing with bacteria: direct addition of bacteria into the fresh concrete; additions in the form of spores, immobilized form onto silica gel or activated carbon, encapsulated form, or using the vascular networks (Talaiekhazan et al. 2014). Concerns about the viability of the endospores within the improper and high pH environment of cement-based materials have led researchers to suggest encapsulation for the endospores. The encapsulation methods consist of enclosing the endospores in a protective covering. Thus, some encapsulation methods such as encapsulation in porous solids, capsule based, vascular based have improved for protecting the bacteria form improper environment conditions. The most generally used method, due to its ease and low cost, is immobilization in lightweight aggregates.

Capsule based approach consists of isolating culture medium inside discrete capsules. Once the capsules are ruptured for example by impact, the healing mechanism is triggered through the release and reaction of the bacteria in the region of damage. When the capsules survived the concrete mixing and casting process, it is vital that they survive within the highly alkaline cementitious matrix and that shell is not influenced by the encapsulated material. Vascular based approach inspired from blood vessels in creatures consist of isolating culture medium in a network of brittle hollow tubes which link the interior and the exterior of the structure. The type of encapsulation technique used effect the maximum allowable crack width which can be healed (Van Tittelboom and De Belie 2013).

## **Results and Discussion**

Bacteria-based concrete is a novel building material, so that physical and chemical properties of bacteria-based concrete need to be revealed by using some tests such as strength, water permeability, ultrasonic pulse velocity, chloride ion permeability, temperature differences. Experimental tests done by researchers showed that mixing bacteria into fresh concrete has some positive and negative effects on concrete properties. In this section, some physical and chemical, observational and experimental results on bacteria-based concrete is discussed.

MICCP ability of bacteria is one of the main subjects for bacteria-based concrete. Repairing of cracks in concrete structure occurs mostly early age, Souradeep et al. (2017) observed that bacteria repairs early age cracks more efficiently than later age cracks. Additionally, relations between healing age and repair rate is shown in Figure 1a where the crack healing ratio decreased remarkably along with the increasing of cracking age (Lou et al. 2015). Repair rate reduced with the extension of cracking age due to death of bacteria or lack of nutrients. It was reported by Rao et al. (2013), life-time of bacteria added directly into concrete mixture is restricted due to continue cement hydration resulting in reduction of cement sand matrix pore-diameter. Moreover, for effective crack healing both bacteria and nutrients mixed into concrete should sustain to continue the integrity of concrete mixture (Rao et al. 2013). According to Vijay et al. (2017), it was observed that encapsulation method protects bacteria from improper environment of concrete so that self-healing efficiency about crack closer and the amount of calcium carbonate precipitation. Bundur and Amiri (2016) mentioned that the chemical admixtures studied herein have no significant influence over the performance of the MICCP applications in bacteria-based concrete.



**Figure 1.** (a) Crack healing ratio of specimens in different cracking age (Lou et al. 2015), (b) the repair rate of specimens with different crack width after different repair time (Lou et al. 2015).

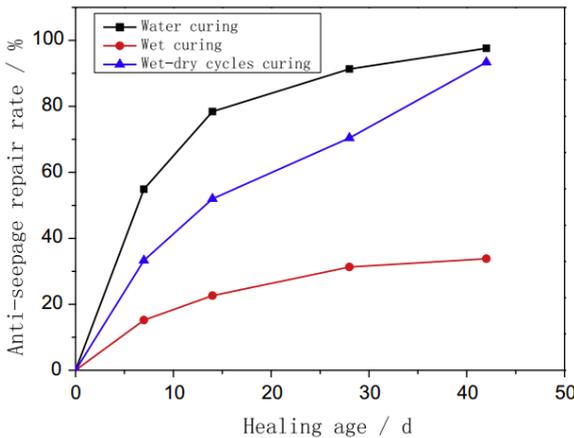
Many researches and Figure 2 support that cracks in bacteria-based concrete specimens fully filled with calcium carbonate provided by crack width up to 0.8 mm (Lou et al. 2015) or 100–200  $\mu\text{m}$  (Souradeep et al. 2017), although it depends on several factors. When the average crack width increases, repairing of cracks are difficult and limited for bacteria repair agent (Figure 1b). To use crack area instead of crack width as measuring cracks was suggested by Souradeep et al. (2017). Not much is known about the interactions between admixtures and MICCP, further researches can be about these relations. It can be visualized by Scanning Electron Microscopy (SEM), which the addition of bacteria into the concrete can enhance cracks in concrete by mineral precipitation. Vijay et al. (2017) observed via SEM analysis that the different calcite crystals embedded with bacteria.



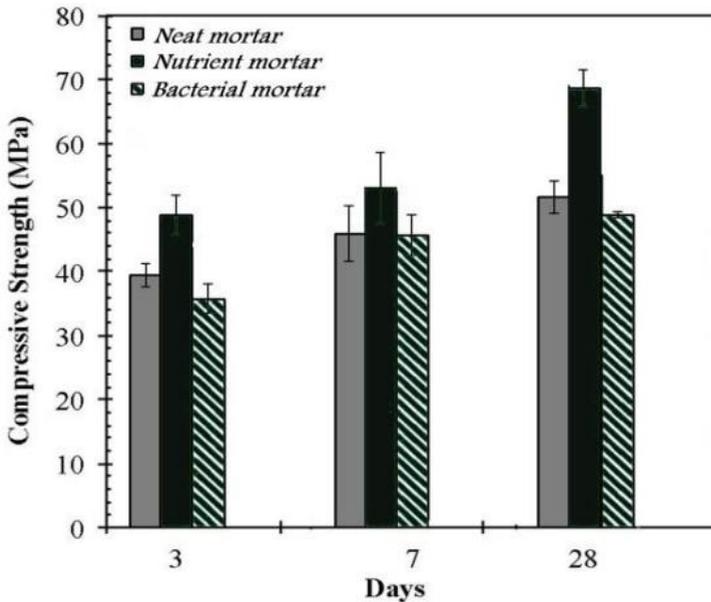
**Figure 2.** Four different pictures of microbiological precipitated calcium carbonate on the concrete cracks, (a) is without magnification, figure (b) with 20x magnification, (c) with 40x magnification and (d) ESEM picture of bacterial activates and precipitation of calcium carbonate with 20000x magnification (Talaiekhazan et al. 2014).

Chloride attacks make vulnerable of the service life of concrete structures. Vijay et al. (2017) were observed that using *Sparcius Pasteurii* and *Bacillus Subtilis* in the concrete

improve chloride ion permeability. Vijay et al. (2017) presented that charge passed in bacterial concrete specimen decreased by 55.8%, 49.9% and 48.4% with respect to normal concrete at the age of 7, 28 and 56 days. Several experimental results were stated that addition of bacteria into the concrete mixture increased water tightness, for the purpose that several researchers aimed to make concrete watertight. Water permeability and water absorption tests assess as a measure of durability (Souradeep et al. 2017). Water absorption depends on such as degree of hydration and fraction of open pores in the matrix. Lou et al. (2015) pointed out that water permeability in the bacteria series was about 10 times lower than that in non-bacteria series. Since, concrete structures may be in a wet condition now of crack appearance, the bacteria should be able to survive under wet conditions. Souradeep et al. (2017) observed that water curing had higher healing ratio compared to samples subjected to wet curing, moreover, for wet-curing the repair rate was slow and became almost same as water curing at late stage. According to Lou et al. (2015), water curing is to be the best way for bacteria-based concrete (Figure 3). Rao et al. (2013) stated that water permeability tests and ultrasound transmission measurements shows that bacteria-based concrete specimens are highly impermeable and have excellent quality compared with controlled concrete specimens.



**Figure 3.** Crack healing ratio under different curing ways (Lou et al. 2015).



**Figure 4.** Influence of corn steep liquor (CSL) medium and bacterial culture on the compressive strength of mortar. The mass ratio of solution to cement (s/c) of 0.45 was used (Bundur et al. 2017).

In many practical application's other properties, such as durability, impermeability and volume stability, may be more important. However, strength of concrete is generally taken into consideration to give an overall picture of the quality. Since structure of concrete has porous, the elastic behavior is very important to guarantee the air and water tightness of the crack and prevent the occurrence of degradation. Retrieve in strength is of less importance, though, if the repaired crack is weaker than concrete matrix, later cracks may appear at the same location where the bacteria agent is already consumed. But, Souradeep et al. (2017) were pointed out that regaining strength was doubtful, since the strength regaining was not remarkably different for live and dead bacteria cells. In a study of Bundur and Amiri (2016), at any day of testing, nutrient mortar samples showed a higher strength than the neat mortar samples, nonetheless, addition of *S. pasteurii* cells in bacterial mortar resulted with a lower strength compared to nutrient mortar (Figure 4). Besides, in this study, they were mentioned that the chemical admixtures used there had no remarkable influence over the compressive strength for MICCP applications in bacteria-based concrete. Table 1 presents a summary of techniques and test results obtained from literature.

**Table 1.** Review of bacterial species, culture media, and major findings.

Species of bacteria used	Culture media	Major Findings	Reference
Bacillus Subtilis	pH $\approx$ 7, at 370C, 105 cells/ml	<p>a) For optimum solution of 35 ml the compressive strength is 39.16 MPa.</p> <p>b) The specimens kept in air have negligible crack filled.</p> <p>c) Water is necessary for successful self-healing.</p>	(Kulthe et al. 2018)
S. pasteurii	urea-corn steep liquor (UCSL), pH $\approx$ 9, 30°C, 107–108 CFU/mL.	<p>a) Industrial waste CSL and bacteria which can be potentially used for self-healing applications in cement-based mortars.</p> <p>b) Substantial retardation was observed in initial setting of samples.</p> <p>c) Addition of S. pasteurii cells with UCSL medium exacerbated the delay initial setting.</p> <p>d) Addition of S. pasteurii cells in bacterial mortar resulted with a lower strength compared to nutrient mortar but did not result with a strength decrease relative to neat mortar.</p> <p>e) The chemical admixtures studied there have no significant influence over the performance of the MICCP applications in cement- based materials.</p>	(Bundur and Amiri 2016)
S. pasteurii	urea-corn steep liquor, pH $\approx$ 9, 30°C.	<p>a) Even though the cracks were closed there was not significant improvement in flexural strength in bacterial mortar samples.</p> <p>b) The compressive strength of bacterial mortar samples was like neat mortar, while it was less than nutrient mortar samples.</p> <p>c) Cracks were fully filled with calcium carbonate in bacterial mortar samples while there was visually no precipitation in neat and nutrient mortar samples.</p> <p>d) The use of waste material CSL did not have any negative impact on bacterial growth and supported the idea of using inexpensive waste material as a replacement for yeast extract.</p> <p>e) Incorporation of UCSL medium delayed</p>	(Bundur et al. 2017)

the initial setting time of cement paste

Spore-forming alkali-resistant bacteria	5.0 g peptone and 3.0 g yeast extract per liter of distilled water, pH = 7.0, 30°C, 10 <sup>9</sup> cells/mL.	a) The crack healing ratio of specimens dropped significantly along with the extension of cracking age. b) The healing ratio of different width cracks was different.	(Lou et al. 2015)
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Souradeep et al. (2017) concluded that strength reduction is basically due to alteration of microstructure because of reducing degree of hydration and poor distribution of hydration products caused by addition of nutrients and microcapsules. According to Bundur et al. (2017), incorporation of *S. pasteurii* cells in bacterial mortar resulted with increasing the compressive strength compared to the neat mortar, and on the other hand, using bacterial cells in bacterial mortar resulted with lower compressive strength than the nutrient sample. Rao et al. (2013) mentioned that a 25% increase in 28-day compressive strength of cement mortar was reached. Bacteria was able to seal flexural cracks as large as 0.3 mm, though there was not any strength regain due to cracks sealing (Bundur et al. 2017). In the present, initial construction cost may be high with using bacteria-based concrete as mentioned in many studies, but if infrastructures are built with bacteria-based concrete that is designed to perform under multiple damages, very low cost may be obtained over the life-time though initial cost may be higher than normal concrete.

## Conclusion

This paper focused on recent advances in the healing of cracks in concrete with bacteria. Bacteria-based concrete that will make a new revolution in the construction industry in the future may be an alternative to conventional concrete. Many researchers have suggested to use bacteria in concrete, due to environment friendly, sustainable process, be healed cracks and be improved concrete durability. The suitable bacteria can resist against improper environment of concrete that would die over time despite of the fact that encapsulated or immobilized in a protective carrier, such as high pH, temperature, serious limitation of water and mechanical forces during concrete mixing, for long durations. Bio-mineralization techniques which reduces the porosity so that CaCO<sub>3</sub> deposition acts as a barrier to harmful substances was confirmed by the experimental results, such as SEM analysis, the water absorption and chloride permeability. Bacteria-based concrete gives promising results in healing and sealing the cracks in the earlier ages of formation of cracks. Efficiency of bacteria-based concrete would mean that the durability and mechanical strength are regained fully or close to that of the normal concrete specimen.

The previous studies show that encapsulation method will present better results than direct application method and shows that bacteria using can improve the strength and durability properties of concrete. It is concluded that using bacteria in concrete improves compressive strength of concrete. While bacteria-based concrete has a lot of positive contribution to concrete properties, there is some problems to be solved in future researches. One of the problems is to find the suitable bacteria and nutrient medium, which can survive a restricted environment of concrete. Shrinkage, corrosion and carbonation properties of concrete need to be studied in detail due to have not been fully understood yet. Although experimental results have shown promising results in the lab, it is important to gather more results for simulating under real conditions such as non-ideal temperature ranges, high salt concentrations and at later ages of concrete element before applying self-healing concrete on a bigger scale. On the other hand, it is very hard to choose most efficient approach, because each research group uses its own test methods to assess the healing efficiency. We suggest developing standard test methods which would be very useful to compare the efficiency of one approach against another. In future studies will need to focus on more interdisciplinary research to produce genetically modified bacteria culture.

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