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Review paper

MICROBIAL SELF-HEALING CONCRETE: A SUSTAINABLE SOLUTION FOR CRACK REPAIR

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Abstract

Concrete is the most commonly used material in the construction sector after water, with an annual production of approximately two tons per person worldwide. Crack formation is a significant issue in concrete structures, leading to reduced service life, increased repair costs, and increased maintenance. Although it is impossible to completely prevent cracks formation, various repair techniques have been developed. Traditional methods pose environmental and health risks. Consequently, there is a growing demand for sustainable solutions such as microbial self-healing techniques that have emerged as a promising alternative, offering rapid, autonomous crack repair while maintaining environmental compatibility. The self-healing effect of bacteria-based concrete acts as a self-sufficient repair mechanism, where bacterial cells initiate the healing process independently, without external monitoring or human intervention. This process is driven by bacterial metabolic activities that produce carbonate ions, which then interact with calcium ions present in the material, resulting in the formation of $CaCO_3$ crystals. This phenomenon, known as microbiologically or bacterially induced carbonate precipitation, plays a key role in enhancing the durability and longevity of concrete structures.

Key words: *self-healing concrete, crack repair, autonomous materials, supplementary cementitious materials, bacteria, microbiologically induced carbonate precipitation*

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1. INTRODUCTION

A small skin cut heals with the protection of a bandage, which allows the body to self-heal. This natural repair process is common in living organisms but rare in man-made materials. In engineering disciplines, material improvement efforts are most often directed toward increasing strength and stiffness, enabling materials to bear higher loads without damage. Over time, these damages can develop into larger cracks that compromise the material's structure and functionality [1]. To increase the service life of engineering structures and reduce maintenance costs, the development of self-healing materials attracts increasing interest from researchers. Concrete, as the most widely used composite material, has proven to be particularly well-suited for the development of self-healing technology. Its multiphase microstructure, porosity, and presence of unreacted particles of cement enable autogenous healing, even without additional interventions. However, natural autogenous processes are generally effective only in sealing microcracks up to 150 μm in width, while larger cracks require application of specially designed autonomous methods, such as shape memory alloys, electrodeposition, capsules, vascular networks, and microbial technologies [2].

Among all available autonomous methods, the use of microbial technologies has shown exceptional potential due to its sustainability, adaptability, and environmental friendliness. Microbial self-healing relies on certain bacteria, primarily bacilli, to induce precipitation of calcium carbonate ($CaCO_3$) via metabolic processes such as ureolysis or nitrate reduction. This biomineralization effectively seals cracks and restores material integrity. This paper analyzes this innovative self-healing approach based on bacterial contribution, focusing on the conditions for cells survival in cement-based composites, methods of bacterial incorporation, their impact on the properties of concrete, and challenges associated with their practical application [3].

2. MECHANISM OF MICROBIAL SELF-HEALING

One of the most widespread natural phenomena present in living organisms is the process of biomineralization. It is a natural process in which living organisms create solid mineral structures, such as the formation of shells and pearls in shellfish, formation of shells in turtles, and formation of bones and teeth in mammals. Biomineralization occurs through a biologically induced mineralization process, in which living organisms trigger the formation of minerals in their surroundings either as an adaptation to environmental conditions or as a product of metabolic activities, such as respiration or digestion [4].

Biomineralization by microorganisms is a process in which microorganisms, most commonly bacteria, unintentionally create mineral structures because of their metabolic activities. In bacteria, the most well-known form of biomineralization is the precipitation of calcium carbonate ($CaCO_3$) through metabolic processes such as ureolysis or nitrate reduction. Metabolic degradation of urea at specific types of bacteria, primarily bacilli (rod-shaped bacteria, usually sporogenic), releases dissolved carbon ions (DIC) and ammonia (AMM) in the microenvironment of cells (Figure 1a). Negatively charged bacterial cell walls attract calcium cations (Ca^{2+}) from the surrounding environment and react with inorganic carbon ions (CO_3^{2-}). As a result of their chemical reaction shown in equation (1), insoluble $CaCO_3$ crystals are formed and deposited on the bacterial cell walls (Figure 1b).

$$\mathrm{CO_3}^{2-} + Ca^{2+} \leftrightarrow CaCO_3 \quad (1)$$

This process can occur within the cementitious matrix, as it contains positively charged calcium ions required for the described precipitation reaction. Over time, the bacterial cell becomes fully immobilized by the precipitated material (Figure 1c), which can seal cracks and strengthen the structure of concrete material. Figure 1d shows the imprints of bacterial cells involved in carbonate precipitation. $CaCO_3$ is considered one of the most suitable fillers for concrete due to its high compatibility with cement compounds [3]. This principle forms the basis for the development of microbial self-healing concrete, and this autonomous approach has shown its effectiveness in repairing cracks of larger widths. The maximum crack width healed in the specimens by bacteria was 970 μm [5].

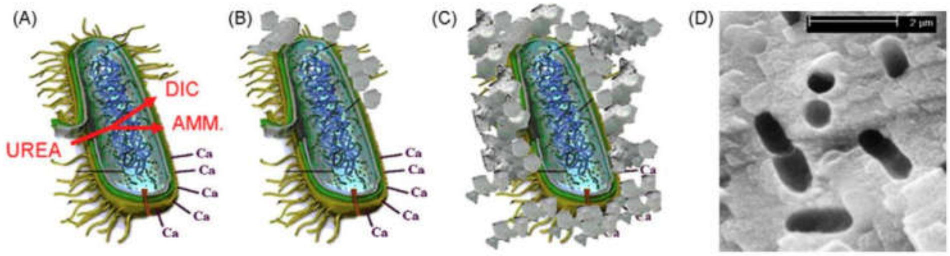

Figure 1. Simplified representation of the events occurring during the ureolytic induced $CaCO_3$ precipitation [3]

When cracks appear, the bacteria, initially in a dormant state, are activated by the ingress of water, multiply and initiate the self-healing process by rapidly producing $CaCO_3$ to seal the crack (Figure 2). Once the crack is filled and the healing process is completed, the bacteria return to a dormant state, remaining inactive until new cracks form and favorable environmental conditions reactivate them [3].

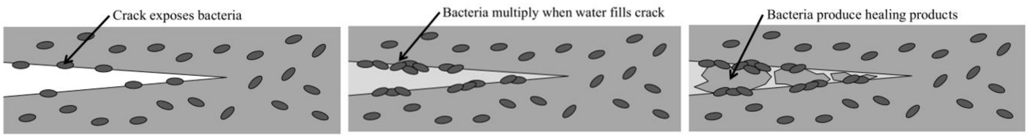

Figure 2. Schematic illustration of bacterial contribution through self-healing approach [6]

3. CONDITIONS AFFECTING BACTERIAL VIABILITY

The efficiency of bacterial self-healing in concrete depends on the production of $CaCO_3$, which is influenced by environmental factors such as pH and temperature. Temperature affects the activity of the urease enzyme, a key catalyst in the hydrolysis of urea, while pH levels also play a crucial role in controlling the availability and efficiency of urease activity. Urea hydrolysis is fundamental to producing carbonate ions, but this process also releases ammonia, which increases the alkalinity of the environment and may inhibit bacterial growth [7]. Any variation in pH or temperature directly affects the rate and extent of $CaCO_3$ precipitation, as illustrated in Figure 3. Given that concrete presents an extremely challenging microenvironment due to its high alkalinity, whose pH values are 12-13 [8], caused by the presence of calcium hydroxide, and elevated temperatures resulting from cement hydration reactions and may reach 70°C [9], bacteria must be able to survive in highly alkaline and thermally unstable conditions to maintain their self-healing function. Elevated pH levels in concrete can cause bacteria to enter a dormant state - spores, which can allow them to survive for up to 200 years, depending on the bacterial strain [10][11]. Dormant cells can return to an active state through a process called germination, which is stimulated by changes in the surrounding environment [12]. However, studies by Šovljanski et al. [13] and Milović et al. [14] have shown that certain bacterial species can perform well and survive extreme conditions in the cement-based matrix, making them particularly suitable for use in self-healing concrete.

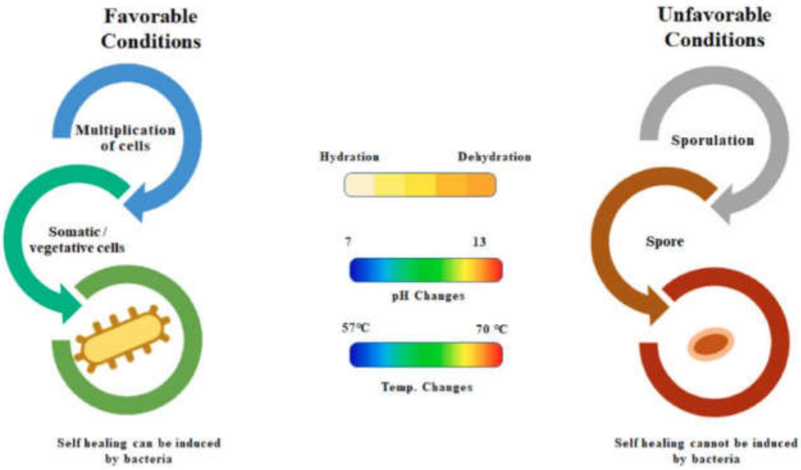

Figure 3. Behavior of bacteria under favorable and unfavorable conditions [15]

Several bacterial species have been identified as suitable for surviving in the highly alkaline environment of self-healing concrete (Table 1). Their optimal growth generally occurs between 30°C and 40°C. It is important to note that, in addition to testing individual bacterial strains, combining strains into co-cultures has also shown significantly improved bacterial growth under high pH and temperature conditions making them particularly valuable for use in bacterial-based self-healing concrete [13][14].

Table 1. The optimum bacterial growth at various pH and temperature levels

Bacteria	pH	Temperature (°C)	References
Sporosarcina pasteurii	11.6	30	[16][17]
Bacillus cereus	7-10	40	[8][18]
B. licheniformis	8-11	37	[18][19]
B. halodurans	12-14	37	[13][18][19]
B. muralis	9	20	[13]
B. simplex	11	37	[13]

4. BACTERIA IMPLEMENTATION

4.1. Direct method

Direct method represents a simple approach for bacteria implementation into self-healing concrete, involving techniques such as surface spraying, injecting bacteria into the crack or directly mixing bacteria with concrete mixture [15].

Despite the simplicity and cost-effectiveness of this method, several challenges can reduce the ability of bacteria to effectively heal cracks:

- Immediate exposure of bacteria to the highly alkaline environment inside concrete leads to a reduction in bacterial viability, and prolonged exposure can impair the germination ability of bacterial spores.
- Shear forces during the concrete mixing process can seriously harm bacterial spores.
- Nutrient availability is often limited within the dense cementitious matrix.
- Cement hydration reduces the diameter of cement matrix pores to 0.5 μm, while bacterial cells are larger in size, 0.5 μm wide and 2-3 μm long.
- Thermal effects during the process of cement hydration can damage active bacterial cells if they are not in spore form [11].

Recent studies by Šovljanski et al. [13] and Milović et al. [14] have shown that direct incorporation can be effective, especially when using robust, alkaliphilic, and sporogenic bacterial strains, such as *Bacillus licheniformis*, *B. muralis* and their co-cultures. These bacteria can survive the highly alkaline environment of fresh cement paste and can remain viable through spore formation over extended periods, even under limited nutrient and moisture conditions. By selecting highly resistant bacterial strains and optimizing initial conditions (such as controlling curing temperature and applying nutrients at later stages), direct incorporation remains a promising and practical method for the application in microbial self-healing concrete.

4.2. Indirect method

Indirect implementation was developed to overcome the challenges associated with the direct implementation method and involves encapsulating bacteria within protective carriers before their introduction into the cement matrix [15]. These carriers provide both physical and chemical barriers, shielding the bacteria from harsh environmental conditions such as high alkalinity, mechanical stresses during mixing, thermal effects during hydration, and limited nutrient availability. Common types of carriers include:

1. **Special Cement Aggregates** – Porous aggregates (e.g., expanded clay, zeolites, lightweight aggregates) for immobilization of bacterial spores and nutrients [20].
2. **Polymer and Special Mineral Compounds** – Microcapsules containing bacterial suspensions or spores immobilized within polymeric shells, as well as silica-based carriers or diatomaceous earth, which offer additional protection (Figure 4) [21].
3. **Special Additives in the Cement Matrix** – Hydrogels, which can serve as reservoirs for bacterial cells and nutrient solutions [22].

Encapsulation allows bacteria to survive the mixing and early curing stages and remain dormant until cracks form and water ingress triggers their activation. However, indirect incorporation increases the complexity of bacterial carrier production and integration, thus also raising the overall cost of material preparation. Based on the above, it can be concluded that both methods, direct and indirect implementation, have their respective advantages and limitations.

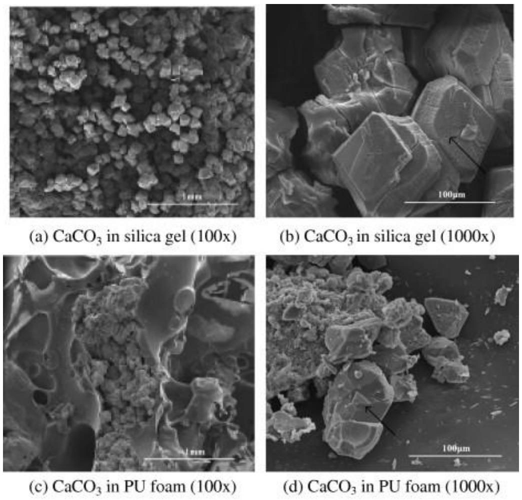

Figure 4. Scanning electron micrographs of $CaCO_3$ precipitation in the silica gel and polyurethane foam [21]

5. KEY FACTORS AFFECTING THE EFFICIENCY OF BACTERIAL SELF-HEALING

The potential of bacteria-based self-healing concrete is influenced by several different factors. Among them, the availability of a calcium source, crack width, crack age, and curing conditions play a dominant role in determining the success and rate of healing.

1. **Calcium source** - the presence of an adequate calcium source is essential for the calcification process to occur. Insufficient calcium availability can limit the extent of healing even if bacterial activity is high. Various calcium salts have been used in research as precursors for mineral precipitation. Initially, calcium chloride was widely used due to its high solubility. However, since chloride ions are detrimental to reinforcement and the long-term durability of concrete, alternative calcium compounds have been explored to ensure a continuous supply of calcium, such as calcium acetate, calcium nitrate, calcium lactate, and calcium di-glutamate [7].
2. **Crack width** - when cracks are wider, the self-healing products may be insufficient to seal them fully. Studies have shown that the effectiveness of bacterial crack healing is limited when the crack width exceeds 970 μm [5]. Figure 5 shows surface images of samples with different crack widths, 300 μm and 800 μm, after various healing periods.
3. **Crack age** - Luo et al. [23] observed that the degree of healing decreased as the crack aged, primarily due to a reduction in bacterial viability within the harsh concrete environment. Newly formed cracks offer more favorable conditions for bacterial activation and precipitation due to better water ingress and nutrient availability. In contrast, older cracks may accumulate dust, contaminants, or undergo carbonation, all of which can inhibit bacterial growth and reduce healing efficiency.
4. **Curing conditions** - especially moisture availability and temperature, are essential for activating bacterial metabolism. A moist environment is critical to

trigger bacterial activity and maintain favorable conditions for ureolytic or nitrate-reducing pathways. Dry curing environments can severely limit bacterial viability and halt the healing process. Similarly, extreme temperatures may negatively impact bacterial survival and enzymatic reactions essential for healing [8].

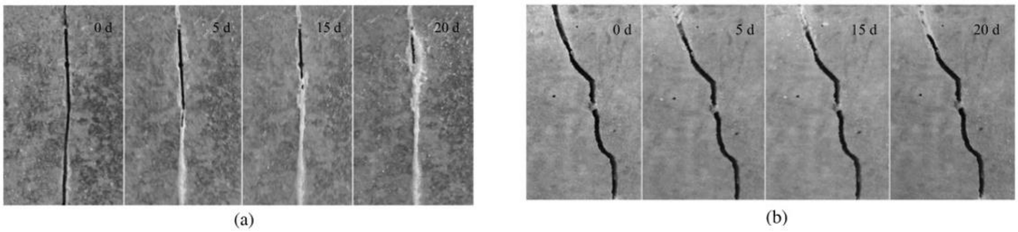

Figure 5. Surface images of specimens with different crack width after different repair time: (a) specimen with an average crack width of 300 μm; (b) specimen with an average crack width of 800 μm [23]

5.1. Efficiency evaluation

The efficiency of the self-healing process in concrete is most directly reflected through the extent of crack closure and the associated recovery of microstructural integrity, durability, and mechanical performance. Cracks that are effectively filled with healing products typically exhibit restored water tightness, enhanced resistance to aggressive environmental agents, and partial or full recovery of load-bearing capacity. Therefore, the evaluation of self-healing efficiency largely depends on the reliable characterization of the crack healing process. Key parameters used to assess crack healing include crack width, length, depth, and number, with crack width being the most critical indicator due to its strong correlation with healing potential. These parameters are commonly measured through optical methods (visual observation) such as high-resolution cameras or optical microscopes [2]. In addition to these efficiency visual assessment techniques, it is important to mention other techniques such as microstructural assessment techniques (SEM, XRD, EDS, TGA), strength recovery and improved durability. Thus, efficiency assessment techniques can generally be divided into four areas: microscopic observation, composition analysis, resistance and durability, and mechanical properties [24].

6. MECHANICAL PROPERTIES OF MICROBIAL SELF-HEALING CONCRETE

Yaveed et al. [15] provided a general overview of the mechanical properties of bacterial concrete, focusing on compressive strength, splitting tensile strength and flexural strength. Different types of bacteria were implemented using the direct method, and a series of samples with varying bacterial cell concentrations were considered for each type. After 28 days of curing, the mechanical properties of the bacterial concrete specimens were compared to those of the control specimens.

6.1. Compressive Strength

Two types of examined specimens, one containing *Bacillus acetophenoni* and the other *Deinococcus radiodurans*, exhibited the highest increase in compressive strength, reaching up to 40.9% at a concentration of 5 × 10^7 CFU/ml [25] and 42.8% at a concentration of 10^5 CFU/ml [26], respectively. The observed specimens with other bacterial strains showed significant variation depending on cell concentration, highlighting the importance of evaluating not only the optimal concentration but also the selection of a specific bacterial strain to achieve maximum compressive strength in self-healing concrete.

6.2. Splitting Tensile Strength

After 28 days, the splitting tensile strength generally showed an increasing trend compared to the control mix across all tested specimen types, with improvements ranging from approximately 10% to 30%. Notably, the specimen containing *Bacillus sphaericus* at a concentration of 10^5 CFU/ml exhibited a remarkable 32.3% increase in splitting tensile strength after 28 days [16]. A similar effect was observed in specimens with *B. licheniformis*, which, when directly incorporated into the concrete mixture at a concentration of 10^7 CFU/ml, demonstrated a 32% increase in splitting tensile strength [27]. It is worth noting that in some mixtures, greater recovery in splitting tensile strength was observed at early curing stages compared to the 28-day results, likely due to the availability of sufficient pore space [28].

6.3. Flexural Strength

In self-healing concrete, the filling of voids with calcification products reduces porosity and results in a denser concrete matrix, which in turn positively affects the improvement of flexural strength [29]. The highest increase was observed in specimens containing *Bacillus subtilis* at a concentration of 10^7 CFU/mL, where the flexural strength after 28 days increased by 45%. Research has shown that, in addition to calcium carbonate precipitation within pores, the acceleration effect of available nutrients - such as calcium lactate, calcium nitrate, and urea—also plays a significant role in enhancing flexural strength [30]. Furthermore, mixtures containing *Sporosarcina sphaericus* within the cell concentration range of 10^0 to 10^7 CFU/mL demonstrated the best results at a concentration of 10^5 cells/mL, with a recorded increase of up to 48% [31]. Based on these findings, it can be concluded that both the choice of bacterial strain and the adjustment of its cell concentration are equally important factors in achieving improvements in the flexural strength of concrete.

7. PRACTICAL APPLICATION IN CONSTRUCTION SECTOR

Developing microbial self-healing technologies has led to an increasing number of real-world applications in the construction industry. Since 2015, several countries, including China, the Netherlands, Belgium, and the United Kingdom, have implemented demonstration projects utilizing bacterial self-healing concrete [15]. Table 2 summarizes notable examples of microbial self-healing concrete applications.

Table 2. Practical application of bacterial self-healing concrete, modified from [15]

Structures	Self- healing agents	Effects
Roof slab of drainage pipe [32]	Anaerobic granular bacteria and mixed ureolytic culture	There were no signs of cracks, but conditions were good for healing.
Retaining wall panel, Highway project [33]	*Bacillus pseudofirmus* spores with calcium acetate and yeast extract	Substantial improvement in panel self-healing after six months.
Mangdao river ship lock [34]	Bacteria spore in powder form with calcium source	No water leakage after 65days, complete healing of cracks.
Irrigation canal [35][36]	Alkali resistant bacterial spores along with yeast extract and calcium lactate	After a year, there were no visible signs of cracks on the lining surface.

8. CONCLUSIONS

Integration of microbial self-healing technologies into cementitious materials represents an innovative and sustainable approach to enhancing the durability and mechanical properties of concrete structures. Through the metabolic activity of specific bacterial strains, primarily of the *Bacillus* genus, calcium carbonate is precipitated and deposited within cracks, effectively restoring structural integrity. This study has provided a general overview of the conditions necessary for bacterial viability, including pH, temperature, nutrient availability and curing conditions, as well as the methods for incorporating bacteria into concrete. Examples of practical applications confirm the potential of these methods for use in the construction industry. However, despite the significant progress achieved in the field of self-healing concrete, there are still certain limitations and challenges in the application of this method, which are outlined below. These include the resistance of certain bacterial species to extreme environmental conditions, such as the high alkalinity and elevated temperatures present in concrete, the long-term stability and reactivation potential of the bacteria, as well as the high cost of producing and preparing bacterial carriers which remains one of the main barriers to broader application in conventional construction. Furthermore, there is a limited number of studies addressing resistance to carbonation, sulfate attack, frost and salt exposure, and there is currently no unified criterion for evaluating self-healing efficiency, as most tests are confined to small-scale material samples, resulting in limited and often inconclusive outcomes. Therefore, future research should focus on further investigation into healing efficiency and mechanisms, as well as exploring alternatives derived from waste materials. Additional focus is needed on selecting and genetically modifying bacterial strains with improved resistance to extreme conditions within the cement matrix, developing new encapsulation technologies that would allow simpler and more cost-effective implementation, and engineering-based modeling of healing kinetics and performance prediction under various service conditions in combination with other smart materials, techniques, and sensors for automated monitoring of damage and the self-healing process. Although various researchers have studied the use of microorganisms in self-healing concrete and investigated their performance, most of these studies have been conducted under laboratory conditions or on small-scale experimental models, meaning that the findings are often based on a limited dataset. These studies rarely consider real-world field conditions, such as geographical and climatic variations, which can significantly influence the effectiveness of microorganisms in practice. This represents one of the major limitations in bioconcrete research and more thorough life cycle assessment (LCA) studies and outdoor applications with enhanced durability are required.

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